

REFERENCE FRAME

Form Follows Function

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The rationale behind the undergraduate curriculum for science students is one of the enduring mysteries of American college and university education. Most science students will major in a single department. That department will require an upper division curriculum that is almost entirely contained within the department in question and will take responsibility for the content of those courses in a more or less rational fashion. Admitting that breadth is of some relevance, that department also sends its students off to take required courses in other related science departments. It names the subjects—and then completely abdicates the responsibility for the content of those courses to the outside departments.

The excuse offered for this procedure is that the content of a *physics* course, for example, must be the responsibility of the physics department, and must certainly not be prescribed by other departments—departments incapable of understanding physics. How can the tradition and mode of thought of physics be properly taught unless a physics department is solely responsible for course content? Let the student be exposed to what physics “really is,” on its own terms, taught in a fashion that is unsullied by considerations of how a particular student might later make use of the insight and understanding gleaned from the course.

The situation is sometimes not as bad as I’ve described. Over the years, an intellectual agreement has been reached between the disciplines of physics and engineering, so that introductory physics courses often serve engineers rather well. The situation is sometimes worse. When an economics department resorts to teaching a course in introductory calculus for its majors, something has gone badly wrong. An educational opportunity has been missed, both by the students and by the faculty.

I recently served on a National Acad-



emy of Sciences/National Research Council (NAS/NRC) committee that attempted to describe an appropriate undergraduate education of a biology student heading for research in the year 2010. (The committee was not charged with addressing the needs of premedical students.) The report, called Bio2010, was published in early September, and is available at <http://www.nap.edu/books/0309085357/html/>. Chaired by Lubert Stryer, the committee had representatives from biology, chemistry, physics, engineering, and mathematics.

Biological quantification

Such a study was needed because biology is becoming much more quantitative and integrated with other sciences. Quantification and a physical viewpoint are important in recent biology research—understanding how proteins fold, how bacteria manage to swim up gradients, how the action potentials of the nervous system are generated, how single-molecule fluorescence studies in cells are possible, how populations of organisms evolve in time, how scanning microscopies work, how contractile proteins generate forces, how patterns can spontaneously be generated by broken symmetry, how DNA sequences coding for different proteins can be arranged into evolutionary trees, how networks of chemical reactions result in “detection,” “amplification,” “decisions.” This list could be a lot longer.

How do colleges and universities meet the challenge of bringing quantification to future biological scientists? My university is perhaps middle-of-the-road in this regard. At Princeton, most biology majors are

premeds, and they are sent off to a physics course that does not require calculus (even though the majority of these students have taken calculus in high school). The students interested in biological research usually also take that physics course. The most mathematically able and physically interested biology students are urged by their advisers to take the usual “physics with calculus” introductory course. Alas, that course was created at the junction between physics and engineering. Its content has been slow to evolve and has not adapted to the current reality and interests *even within physics itself*. For example, the move of physics towards complex systems is totally ignored. The second half of the course is chiefly a headlong rush toward Maxwell’s equations. The course contains very little physics of the past 50 years, and has no content visibly connected to any of the interesting ideas I mentioned in the previous paragraph. Should we be surprised that biology students who take this course view it only as a requirement and, if later asked about its content, remember rather little?

The amount of beautiful real physics that might be presented to students is overwhelming. *Why not choose from this wealth of materials only subject matter that is either directly relevant to modern biology or is essential for pedagogy before the more relevant materials are developed?* Faced with such an opportunity, the physics and engineering panel of the Bio2010 committee (Daniel Axelrod, Scott Fraser, Jonathan Howard, Mimi Koehl, Carl Luchies, Jose Onuchic, Viola Vogel, and I [chair]) used a zero-base budgeting approach to design an appropriate physics course. We ignored traditional curricula and began with a blank sheet of paper.

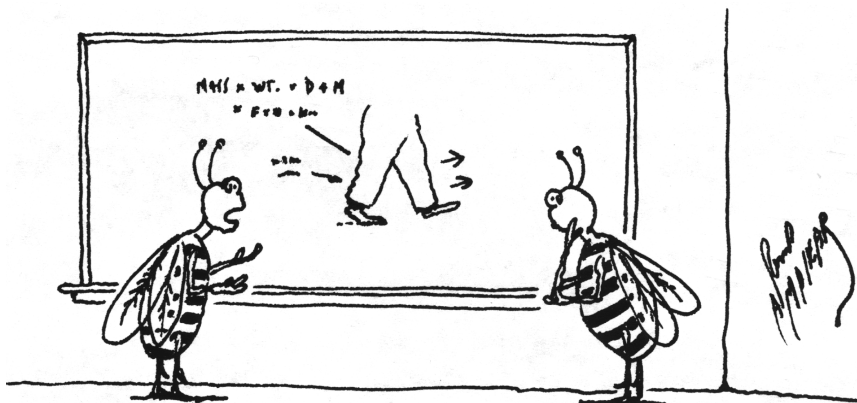
The *idea* of equations of motion is in; a course would probably begin with mechanics as the basis for the later subjects of molecular statistical mechanics and statistical dynamics. The *idea* of a conservation law (and the particular examples of the conservation of energy and momentum) is in. Angular momentum is out; the

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available time does not permit the luxury of enumerating all conservation laws. Thermodynamics is in, with most of the emphasis in thermal physics placed on the behavior of classically described molecular systems and on the relation between classical physics and the behavior of large molecules. (Understanding ideal rubber is as beautiful a piece of physics as understanding an ideal gas.) Relativity is out. Electrostatics, important to molecular structure, is in. Complex behavior of simple physical systems is in, and with it the *idea* of constructing new quantitative models as a part of science. (At an elementary level, contrast doing laboratory experiments on a rapidly moving object and then finding a useful model of hydrodynamic turbulent forces with the usual physics laboratory experiment on a falling body.) Magnetism, irrelevant to most of biology, is out. Waves, optics, and spectra are in. And so on. Although a particular institution might well devise a somewhat different list, it is imperative for all to develop a curriculum based on the new needs and the changes in the style of both physics and biology.

The idea of the *function* of a "material object" is present in biology, present in engineering or applied science, but absent in pure physics and other physical sciences. In pure physics, a proton has no function; in geology, a mountain has no function. To the applied scientist designing a laser, a neon atom in a helium–neon laser has a function. Modern biological research is in great part about *understanding function*—how systems attain their *overall function*, or the *functional role* of a subsystem. Analyzing and understanding functional systems having known and simple components can be a highly useful prelude to the biological research problem of analyzing systems with unknown components, incomplete component lists, or unknown functions. The conservation of total student effort—another important conservation law—precludes sensibly devoting an entire course to an engineering discipline. Using part of the introductory physics laboratory as a vehicle for experimenting with, designing, and analyzing *functioning* systems based on physics is a suitable solution to the educational problem.

At some universities, there may not be enough biology majors interested in biology research to support a course especially for them. However, such a course would also serve most chemistry majors better than the usual introductory physics course does. The



"According to all known laws of physics it should be impossible for them to walk!"

more quantitatively inclined premeds would certainly find the new curriculum of greater interest and benefit than the customary "physics for engineers" curriculum.

What about potential physics majors? Face it, many universities have a curriculum for physics majors that *requires introductory physics* but makes no use whatsoever of any specific knowledge contained in the introductory course—all the material of introductory physics is taught anew at a higher level. The introductory course serves chiefly a metapurpose, namely, to teach the relationships among experimental measurement, descriptions in words, and mathematical or computer-based analysis and modeling. The physics material in the Bio2010 curriculum is at least as suitable for this metapurpose as the material of the usual curriculum. In recent years, the number of physics majors who go on to research in biology and other complex systems (whether as members of a physics department or other departments) has been steadily increasing. In my opinion the number should increase, because for many students an education emphasizing physics is the best available undergraduate base for continuing on to research in biological or other complex systems. The availability of such an introductory course, in conjunction with changes in the teaching of biology, might actually increase the number of physics majors.

Parallel changes are also needed in mathematics and computer science. New mathematical curricular items described in the Bio2010 report include the computer science concept of an algorithm, computability, information theory, stochastic processes, and structural relationships in data. The biggest single qualitative change is the emphasis on discrete mathematics, usually absent in the elementary mathematics curriculum for science majors. To cover in three semesters calculus, dynamical

systems, and linear algebra as well as these topics presents introductory mathematics with as difficult a challenge as that presented to introductory physics. Mathematics too will be faced with the need to discard treasured traditional anachronisms in favor of material relevant to modeling biology and other complex systems. The artificial instructional boundaries between mathematics, computation, and computer science will need to be destroyed.

The impact of such a curriculum change for introductory physics and mathematics will be enormously larger if biology departments also mend their ways and begin teaching introductory biology with much more emphasis on quantification and modeling. Because more new material has, overall, been added to the curriculum than old material has been removed, I believe that the curriculum can be effectively implemented in a four-year period only if there is strong coordination of the content of the diverse courses in all departments. This coordination might include placing more reliance on the content of high-school Advanced Placement courses, which are too often unnecessarily retaken in college.

The Bio2010 report addresses, within the all-too-obvious limitations imposed by having been written by an NRC committee, the entire range of curricular issues. I urge you to read its relevant parts and to ask how your institution and your undergraduate physics curriculum can best accommodate to this century. Individual institutions have distinct clienteles, academic politics, and resources. Material that is in a physics course in one institution may be in a biology or chemistry course in another. There should be a diversity of responses to the report. Our report is not a recipe. But it describes a challenge too important and too interesting to ignore. The challenge is not just to help the biologists. It is also to help ourselves. ■