Physics for (molecular) biology students

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Over the last decade or so there has been an ongoing discussion about how to best teach scientific subjects (see (Powell 2003; NRC 2011)). This has led to significant activity in the area known as DBER (discipline-based education research) (NRC 2012). While few would now argue that a lecture-only approach is appropriate for most topics, what seems to have been, rather surprisingly, neglected are the intra- and inter-disciplinary discussions needed to define what a coherent curricula look like (Klymkowsky and Cooper 2012). What can, realistically, be conveyed to students in the time (credit hours) available? What topics are primary and which secondary or, except in highly specialized situations, superfluous, and what amount of time and practice is required by students to achieve the subject mastery expected of them? These are questions that require objective data (rather than personal empiricism) to answer. The answers to these questions are of practical importance for all students, particularly since a curriculum perceived, rightly or wrongly, to be designed to drive the "undeserving" out of a subject area produces unnecessary obstacles to inclusion and learning (Mervis 2011). A coherent, engaging, and rigorous curriculum is particularly critical for those students whose undergraduate experiences do not extend into graduate studies; here I am thinking specifically of students who will become science teachers. With various efforts to generate new (next generation) K-12 science standards (see (NRC 2012)), it becomes increasingly critical that students, that is, future science teachers, are adequately prepared to teach their disciplines in order to achieve the level of student understanding that these standards call for. Rather sadly, this is rarely an outcome that is foremost (or even secondary) in the thinking of disciplinary college science departments, deans, and provosts. If the situation is one of benign neglect or complacency within disciplinary departments, it is even more pernicious when these courses are taught to majors in other departments.

Let me present the case that I am most familiar with, molecular biology students. One could argue, convincingly I think, that together with an understanding of evolutionary mechanisms (surprisingly, a topic rarely addressed within the typical molecular biology curriculum), molecular biology forms the foundation for all of the various biological disciplines (Klymkowsky 2010). More and more molecular methods are used in these areas, both in the context of experimental manipulation and outcomes analyses. That said, it is often difficult to discern exactly what topics, and to what level of resolution, a typical molecular biology curriculum covers, or what level of working understanding students achieve. The problem is, if anything, more severe when it comes to the extra-disciplinary courses that are required of students: typically, these include a semester or two of calculus, generally delivered through courses designed for physics or engineering students, two semesters of general chemistry, often organized around a death march through buffer and stoichiometry problems, followed by a semester or two of organic chemistry, often taught from the decidedly abiological perspective of a synthetic chemist, one or two semesters of biochemistry, and a semester or two of physics. These latter physics and chemistry courses are rarely designed to meet the needs of biology students, and in many cases, little thought has gone into articulating exactly why students should be required to take them. Without a compelling justification such requirements are akin to a doctor (the disciplinary faculty) prescribing a drug (a course) for a disease the patient (the student) does not actually have — a form of medical (pedagogical) malpractice. To follow the analogy further, we need to recognize the fact that all drugs have unwanted consequences.

In part to address the issue of relevance, over the past six years I have been working with Melanie Cooper (Michigan State University) to consider whether the structure of the typical general chemistry course addresses the disciplinary needs of the students who are required to take it. This analysis included both chemistry majors and students from other departments. The result of this process is a new general chemistry curriculum: Chemistry, Life, the Universe, and Everything (CLUE)(Cooper and Klymkowsky 2013). The development of the CLUE textbook and course materials was based on a rather intensive process that included many discussions about what chemical ideas were central - the resulting course is not "chemistry for non-majors" but rather a conceptually rigorous approach to the core ideas and skills required to understand chemistry. It involved going beyond course transformation (from lecture to various types of "active learning") to a thorough consideration of content and performance expectations

(Klymkowsky and Cooper 2012). Through comparative and longitudinal studies we have found clear evidence that the CLUE course improves student understanding of key concepts in chemistry and that these effects persist into organic chemistry (Cooper et al. 2010; Cooper et al. 2012; Cooper et al. 2012; Underwood and Cooper in preparation.)

All of which, finally, brings me to the point of this essay - a call for an analogous discussion to define the physics content that is needed by, or better put, would justify a molecular biology department requiring its students to take an introductory physics course or two. An aspect of such a discussion that is worth explicitly acknowledging is the general asymmetry between molecular biology faculty and their physics and chemistry colleagues. For example, my own degrees are in biophysics, which entailed my taking a number of mathematics, physics, and chemistry courses. Most biologists have taken a similar mix of courses (see above). Yet, few physics (or chemistry) faculty have ever taken a single course in biology, much less the course sequence needed to have even a passing familiarity with the concepts and skills employed in understanding, doing, and/or teaching modern biology. This makes the conversation rather skewed, if it occurs at all. More often than not physics faculty are called on to imagine what makes physics relevant to biology students, without a clear appreciation of core biological concepts. Attempts to make physics "relevant" can lead to the inclusion of cartoonish biological examples (blood flow in giraffes or spherical cows). While it is clear that physical principles are involve in a range of physiological processes (see for example (Vogel 2013)), physiology is not the most important aspect of modern biology and most molecular biology programs do not seriously consider the physical constraints on macroscopic systems (whether they should or not is another question). Understanding what is and what is not central to modern biology requires candid conversations between biologists and physicists, a realization reinforced by my experiences at the 2014 Introductory Physics for Life Sciences conference and the 2014 Gordon Research Conference on Physics Research and Education.

So what does a biology student, not to mention a working molecular biologist, need from a physics course? First, and rather emphatically I would reject the premise that physics per se is generically useful to understanding molecular biology. A poorly designed course, perceived as irrelevant to the disciplinary interests or needs of students could be viewed as an inappropriate imposition. What we need is a more explicitly relevant, molecular-level approach to the physicochemical foundations of non-equilibrium systems whose detailed organization and behaviors reflect their evolutionary history, that is, organisms (Mayr 1985). It is clear that the structure of atoms determines the nature and shape of the molecules they form. Why carbon is tetravalent is a physics question. While one might argue that bond formation lies within the purview of chemistry, the charge distributions within molecules determine how those molecules interact with one another, including the relative strengths and specificities of those interactions, a topic reasonably considered the focus of physics. Here the effects of thermal motion play a key role; the probability that an intra- or inter-molecular interaction will persist over time will depend upon collision kinetics, which of course relies on Newton's laws of motion.

Understanding these topics involves a clear presentation of the concept of energy and the laws of thermodynamics, including the impact of system-level entropic factors. Energy itself is a complex and ill-defined concept (see (Cooper and Klymkowsky 2013)).[1] Here we are particularly concerned with system behaviors, behaviors that emerge from the molecular and produce the macroscopic. Biology, at all levels, is about the behavior of complex, non-equilibrium systems (Alon 2003; 2006; Klymkowsky 2010). If we think about where ever a reaction occurs, whether it is the separation of oil and water to the synthesis of deoxyribonucleic acid, the "expression" of a gene, the folding, assembly, and behavior of proteins and molecular machines, or the transfer of information over time and space, we are talking about reactions characterized by both enthalpic and entropic effects. Much of the self-organizing behavior observed in biological systems, from the formation of membranes to the folding of proteins is based on entropic drivers. Moreover, in addition there are stochastic, but functionally significant effects that arise from the small number of interacting components often at play (see (Alon 2003; Ansel et al. 2008; Shahrezaei and Swain 2008; Eldar and Elowitz 2010)). The typical macroscopic physic course ignores such processes. So the question becomes, how to incorporate them into a physics course relevant to molecular level biological processes?

As a biologist it is not for me to design this type of course, it is for physics faculty. But I would propose that just as the collaboration between a chemist and biologist has been highly productive in the redesign of a general chemistry course, so a collaboration between physicists, chemists, and biologists would be extremely useful in designing a relevant, rigorous, and effective physics course that would serve both as an introduction to modern physics and which biology (and biochemistry) departments could, with a clear conscience, require their students to take.

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[1] It was an interesting experience to listen, as part of an NSF-funded project on the design of a thermodynamics course, to the often heated discussions between physicists and chemists on the relationship between potential and chemical energy.

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