Teaching Physics to Life Science Students – Examining the Role of Biological Context

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Abstract. We describe a research agenda to inform renovating the introductory physics course commonly taught to life science majors. The theoretical framework of the renovation is the cognitive apprenticeship model, in which learning occurs most effectively in an environment of expert practices so that students can articulate why their learning matters. This model is supported by studies of transfer that suggest for students to successfully apply physics to another field, they need practice making such applications. Guided by this theoretical framework, we have begun to restructure our introductory physics courses for these students around biologically rich contexts — examples in which fundamental physics plays a significant role in understanding a biological system — to make explicit the value of physics to the life sciences. This requires restructuring the course content to reflect the topics most relevant to biology. In this paper we describe our approach to this course, identify research directions addressing (1) the role of biological context in learning for these students and (2) issues in implementing such a course for physics faculty, and summarize preliminary results.

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WHY TEACH PHYSICS IN BIOLOGICAL CONTEXT?

As knowledge of the mechanisms of biology increases, and as physics-based technology permeates both biological research and clinical medicine, national reports from the life science [1] and medical [2] communities stress the importance of a deeper understanding of fundamental physics content and a higher level of problem solving and mathematical skills than commonly expected of biology and biochemistry majors and premedical students ("life science students"). Typically these students take a year-long introductory physics course that covers the same content and uses the same approach as the course for engineering and physical science students, but expects less sophisticated problem-solving skills and qualitative reasoning, and uses a lower level of mathematics. Students are told this course is required because it will help them understand their chosen fields; they are often skeptical, to say the least.

These courses rarely demonstrate how the ideas and intellectual tools of physics apply to the life sciences. If a few biologically related examples are included, they rarely reveal how physics gives insight into biology. Fundamental concepts such as energy and entropy are usually taught with a restricted focus that makes them irrelevant to biology. Finally, essential topics for biologists, such as fluid statics and dynamics, diffusion, and the effect of dielectrics on electrical interactions, are usually taught superficially or omitted altogether.

Research on learning suggests that placing physics in biological context is critical for life science students to best learn physics. For example, the cognitive apprenticeship model of student learning stresses the importance of placing the subject matter in a context that is meaningful to the student, in order to create an environment of expert practice. [3] For students motivated by biology or medicine, this implies that an effective introductory physics course should anchor physics principles in meaningful biological contexts. Furthermore, transfer studies [4,5,6,7] suggest that if a goal is for students to apply physics in another scientific field, it is important to include such applications in the learning process.

Given such a compelling motivation, why is there no widespread sophisticated introductory physics for the life sciences (IPLS) course with an optimized syllabus embedded in biological contexts? Such courses have been developed in the past [8] but have not become widespread. There are many challenges in developing and establishing such an IPLS course. This paper summarizes a subset of those challenges that need research, and describes our efforts addressing some of those questions by giving preliminary results from our modified IPLS courses.

Currently there is renewed interest and effort in IPLS development both within the PER community and among physics educators more broadly, and a great deal of outstanding work is underway. [9]

However, the research and development necessary to widely establish this course will require the effort of many. We hope that this paper, by laying out the need and the research agenda, helps inspire increasingly broad PER efforts and collaboration in this direction.

In addition to the research questions outlined below, the physics topics, scientific skills, and modes of thought explicitly taught in the course must be carefully selected in consultation with life science and medical professionals, balancing the topics and skills most needed for the life sciences with established research into effective teaching of physics content and skills, and the construction of a coherent view of physics as a discipline. The course must equip students to use the intellectual tools of physics — it must genuinely be a physics course, not a physical biology course. Describing in detail the process for making these choices, and the resulting curricula, is very important but beyond the scope of this paper.

IPLS AT MINNESOTA AND SWARTHMORE

Minnesota and Swarthmore span a large range of teaching environments, faculty, and students. Both offer a calculus-based course in introductory physics for life science students. This course has been recently modified to focus on the most important topics for this student population, based on information from biology faculty at the institution as well as national reports. At Minnesota, this is a year-long course; at Swarthmore, a standard first semester of introductory physics is followed by a modified second semester.

In the modified courses, each topic is organized around a small number of important biological examples chosen in consultation with our life science colleagues. Typically biological examples are more complex than examples commonly used to teach introductory physics, so it is critically important to balance the need for biological context with the use of simpler, effective physics examples. Furthermore, in presenting biological examples, the process of making simplified physical models of complex systems must be made explicit. [10]

Our typical instructional sequence is as follows:

- Each physics principle is introduced using a biological example to set the context: why is this particular principle important for biology? This is often framed in terms of a problem to be solved.
- The instructor applies the physics principle to some simpler physics contexts, preferably with a connection to students' previous experience. [11] Research-based activities such as ConcepTests, ranking, and comparison tasks are used to develop conceptual reasoning. These are placed in biological context when possible.
- New physics principles are explicitly linked with previous principles by solving Context-rich Problems throughout the course. These problems also connect to the biological context when possible.

For example, the contexts provided for geometric optics are vision (including vision correction) and microscopy (confocal microscopy brings together geometric and wave optics [12]). Teaching image formation with lenses and lens combinations begins with established PER-based physics examples. [13] However, there are important differences between how physics courses typically approach lenses and how lenses operate in biological contexts. To give just one example, the human eye includes an adjustable focal length lens at a fixed distance from the retina; for an image to be perceived as focused, it must form on the retina, and hence at a certain image distance. In most physics courses, image formation problems involve lenses with fixed focal lengths and variable image distances. In our courses, ConcepTests and Context-rich Problems (provided online [14]) are used to explore these biologically appropriate scenarios as well as more standard physics scenarios, aided by a problem-solving laboratory in which students devise and test models of vision correction and microscope focusing. Other examples of biological contexts and a detailed syllabus are also provided online. [14]

PROPOSED RESEARCH AGENDA

We identify three broad research programs needed to inform development of such IPLS courses. Is teaching physics using biological contexts as effective for students as the theoretical basis suggests? What are the characteristics of effective biological contexts? What is required of IPLS courses so that ordinary physics faculty will teach them? These research programs are not exhaustive; work must also be done to better characterize the student population. [14]

Effectiveness of Teaching Physics in Biological Context

The cognitive apprenticeship theoretical framework raises the following research questions:

1. Do students find physics taught in biological context more motivating than a traditional course?
2. Do students' attitudes toward learning physics improve compared to a traditional course?
3. Do students learn the physics content and develop quantitative and qualitative skills better than in a traditional course?

4. Are students able to apply physics in their downstream biology courses and research?

Affirmative answers to the first two questions are probably necessary but not sufficient for affirmative answers to the latter two. These first two questions can begin to be addressed through existing attitude surveys, such as the CLASS [15], as well as more targeted survey questions and interview techniques. The third will require both using existing assessments over appropriate content [16,17] and skill [18] domains, and developing and validating assessments for areas in which they do not yet exist. [19] The fourth requires new instrumentation that must be based on an analysis of both existing and desired biology courses. One step in this direction would be to develop an artifact-based interview protocol to probe student recognition of physics principles in a biology course.

Designing Effective Biological Contexts

A critical question for developers is: What characteristics make biological contexts effective for:

1. learning fundamental physics content and reasoning skills (*i.e.*, model building, problem solving)?
2. creating an environment of expert practice?

To address these questions, a set of biological contexts needs to be constructed that supports a coherent physics course. These contexts must demonstrate the value of both the fundamental physics principles and reasoning skills that are to be learned in the course. We hypothesize that beginning with the most effective contexts may also aid in creating the environment of expert practice. Assessments of student understanding of the targeted fundamental physics principles and skills need to be designed based on interviews of students, examining appropriate written work, and appropriately designed concept inventories. Interviews can also provide data on whether an environment of expert practice has been created in the student's mind. Based on such assessments, the contexts used can be refined or changed in the course design process. The goal is to produce guidelines for future developers for designing effective biological contexts.

Designing a Readily Adoptable Course

Previous work by the University of Minnesota Physics Education Group and collaborators [20,21] indicates that to facilitate adoption, a curriculum must:

- be congruent with strongly held instructor beliefs and values about teaching physics,
- produce improvements in student learning or behavior that are directly observed by the instructor,
- be adoptable with reasonable effort, and
- degrade gracefully, so that less-than-ideal implementations are still reasonably successful.

For IPLS courses to become widespread, it will be particularly important to identify whether modified syllabi and/or biological contexts violate any strongly held instructor beliefs or values, by interviewing faculty who have not taught this course using artifact-based techniques. [22] Furthermore, faculty who test the course materials should be monitored and interviewed to determine (1) the effort (actual and perceived) required to teach the course and (2) their perception of the course's effectiveness at engaging students and fostering understanding of physics.

PRELIMINARY RESULTS

Student attitudes. At Minnesota, student attitudes toward learning physics were measured with the CLASS [16] in both the redesigned course and a more traditional course. In the first semester, the redesigned course showed a pre/post gain of 3±2% (more expert-like attitudes); the other showed a decrease of 7±2% (less expert-like attitudes). In the second semester, the redesigned course showed a gain of 9±2% and the other showed a decrease of 6±2%. While the gain was small, it is noteworthy because introductory physics courses typically show a decrease. [16]

At Swarthmore, an evaluator from the biology department [23] surveyed the students on their interest in and appreciation of the role of the biological contexts in the modified physics course. He found significant agreement with statements such as "Including biological examples helped me enjoy physics more than if we had used non-biological examples" (3.6 ± 0.1 on a scale of 1 to 4, 4 = "strongly agree"); "Understanding aspects of physics that we learned in this course are useful for solving real-world problems in medicine, agriculture, the environment, and other topics in biology" (3.4 ± 0.1); and "This course helped me think about biology in useful new ways" (3.4 ± 0.1). This trend of positive attitudes toward the course was supported by comments on course evaluations and unsolicited student feedback. A CLASS study is underway at Swarthmore.

Content learning. To test content learning, existing conceptual inventories were used (the FCI and the BEMA). At Minnesota, data have been obtained for both the previous course and the redesigned curriculum. No attempt was made to control for student variation except statistically in these classes of about 200 students. The data are suggestive. For two offerings of the redesigned course with two different instructors, the FCI pre/post gains were 25±2% and

20±2%. For comparison, faculty not using this curriculum had FCI gains of 10±2% and 11±2%. In the second semester, the pre/post gain obtained for concepts using the BEMA was 30±2% for the redesigned course and 11±2% for the standard course.

At Swarthmore, BEMA results from two offerings of the reformed class show gains of 33±2% and 38±2%; the same student population in a traditional class had a gain of only 24±3%, with higher pretest and lower posttest scores. [24]

Although these preliminary results are consistent with our hypothesis, existing conceptual surveys are poorly matched to the content most important for these students — hence the need for more suitable assessment instruments. For example, the FCI does not test fluid mechanics, oscillations, thermodynamics and statistical physics, arguably the most important first semester topics for biology students; the BEMA does not test optics or electric fields in dielectrics.

CONCLUSIONS

We have put forward a research program whose results will support the design of an effective and adoptable IPLS course, based on the theoretical framework of cognitive apprenticeship. Preliminary results at our two very different institutions suggest that teaching physics in biological context for life science students is a sound and promising approach. Based on both our findings and the efforts of many others elsewhere, we encourage PER researchers to contribute to this effort.

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REFERENCES

1. *BIO2010: Transforming Undergraduate Education for Future Research Biologists,* Committee on Undergraduate Biology Education, National Research Council (National Academies Press, 2003).
2. *Scientific Foundations for Future Physicians: Report of the HHMI-AAMC Committee* (American Association of Medical Colleges, 2009).
3. Collins, Brown, and Holum, American Educator **6** (1991).
4. Perkins and Grotzer, American Psychologist **52**, 1125 (1997).
5. Detterman, "The case for the prosecution: Transfer as an epiphenomenon," in *Transfer on trial: Intelligence, cognition, and instruction*, Detterman and Sternberg (Eds.), 1 (1993).
6. Halpern, American Psychologist 53, 449 (1998).
7. Schwartz, D. L., Bransford, J. D., & Sears, D. (2005), "Efficiency and innovation in transfer," in J. Mestre (Ed.), *Transfer of Learning: Research and Perspectives*. Information Age Publishing.
8. For example, Benedek and Villars, *Physics With Illustrative Examples From Medicine and Biology*, Addison-Wesley (1979); Bruinsma, "UCLA Physics for Life Science Majors," course notes published by Hayden-McNeil (2006); and the *Humanized Physics Project* (http://physics.doane.edu/hpp).
9. See for example the programs for the sessions "Reforming the Introductory Physics Course for Life Science Students" held at the AAPT national meetings since Summer 2009 (at http://www.aapt.org/AbstractSearch/) and the IPLS Wiki (http://www.phys.gwu.edu/iplswiki/) with documents from the NSF-funded 2009 workshop.
10. Clement, J., J. Res. Sci. Teach. **30**, 1241-1257 (1993).
11. Hestenes, D., Am. J. Phys. **60,** 732-748 (1992).
12. Catherine H. Crouch, "Capstone examples for second semester IPLS," Winter 2011 AAPT meeting, online at http://materials.physics.swarthmore.edu/IPLSTalks.
13. At Swarthmore, instruction draws upon the University of Washington "Convex Lenses" tutorial (McDermott, Shaffer and the UWPEG, *Tutorials in Introductory Physics* (Prentice Hall, 2002)) among other sources.
14. These materials are available at http://materials.physics.swarthmore.edu/IPLSMaterials.
15. For example, J. E. Watkins, K. L. Hall, J. E. Coffey, T. J. Cooke, E.F. Redish, "Understanding how students use physical ideas in introductory biology courses," Winter 2011 AAPT meeting.
16. Adams, Perkins, Podolefsky, Dubson, Finkelstein, and Wieman, PRST-PER **2**, 010101 (2006).
17. Hestenes, Wells, and Swackhamer, The Physics Teacher **30**, 141 (1992).
18. Ding, Chabay, Sherwood, and Beichner, PRST-PER **2**, 010105 (2006).
19. Docktor, J., & Heller, K. (2009), "Assessment of Student Problem Solving Processes," in *AIP Conf. Proc. Vol. 1179: 2009 PER Conference* (pp. 133-136). Melville, NY: AIP.
20. The authors are aware of fluids concept inventories under development by Jamie Vesenka, Dawn Meredith, and Kelvin Chu, and by DJ Wagner.
21. Yerushalmi, Henderson**,** Heller, K., Heller, P., Kuo, Phys. Rev. ST: PER **3**, 020109. (2007)
22. Yerushalmi, Cohen, Heller, K., Heller, P., Henderson, C., Phys. Rev. ST: PER **6**, 020108 (2010).
23. Henderson, C.**,** Yerushalmi, E., Heller, K., & Heller, P., Kuo, V., Phys. Rev. ST: PER **3** (2), 020110 (2007).
24. Survey designed and administered by Philip Kudish, Swarthmore College Department of Biology.
25. Graphs of the data given in this section, with pre and post scores, are provided in the poster at http://www.per-central.org/perc/2011/files/PERC2011_IPLS_poster.pdf.