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Essay

Competency-Based Reforms of the Undergraduate Biology Curriculum: Integrating the Physical and Biological Sciences

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The National Experiment in Undergraduate Science Education project funded by the Howard Hughes Medical Institute is a direct response to the *Scientific Foundations for Future Physicians* report, which urged a shift in premedical student preparation from a narrow list of specific course work to a more flexible curriculum that helps students develop broad scientific competencies. A consortium of four universities is working to create, pilot, and assess modular, competency-based curricular units that require students to use higher-order cognitive skills and reason across traditional disciplinary boundaries. Purdue University; the University of Maryland, Baltimore County; and the University of Miami are each developing modules and case studies that integrate the biological, chemical, physical, and mathematical sciences. The University of Maryland, College Park, is leading the effort to create an introductory physics for life sciences course that is reformed in both content and pedagogy. This course has prerequisites of biology, chemistry, and calculus, allowing students to apply strategies from the physical sciences to solving authentic biological problems. A comprehensive assessment plan is examining students' conceptual knowledge of physics, their attitudes toward interdisciplinary approaches, and the development of specific scientific competencies. Teaching modules developed during this initial phase will be tested on multiple partner campuses in preparation for eventual broad dissemination.

INTRODUCTION

A growing series of reports on undergraduate life sciences education (e.g., National Research Council [NRC], 2003; Steen, 2005; Project Kaleidoscope, 2006; American Association for the Advancement of Science [AAAS], 2011; Association of American Universities, 2011; President's Council of Advisors on Science and Technology, 2012) has found standard curricula sorely lacking in both content and pedagogy. There is strong evidence that traditional didactic instruction is ineffective, but most science courses are still taught from a strict disciplinary focus, using predominantly teacher-centered and content-focused instructional approaches. Despite a strong consensus among scientists and educators on the need for change, the pace of broad educational reform has been frustratingly slow (Wieman *et al.*, 2010).

One perceived impediment to undergraduate life sciences education reform has been the very specific course requirements of the medical school admissions process. Because the majority of life sciences students are contemplating careers in the health professions and therefore must complete premedical course prerequisites as part of their undergraduate education, the biology and life sciences majors at many institutions reflect a curriculum heavily prescribed by medical school admissions requirements. Institutions have generally been very reluctant to make major changes in the undergraduate life sciences curriculum for fear that their students

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Table 1. Examples of concepts and skills relevant to the physical sciences that will be emphasized on the 2015 revision of the MCAT[a]

Foundational concept 4. Complex living organisms transport materials, sense their environment, process signals, and respond to changes using processes understood in terms of physical principles.
4A. Translational motion, forces, work, energy, and equilibrium in living systems
4B. Importance of fluids for the circulation of blood, gas movement, and gas exchange
4C. Electrochemistry and electrical circuits and their elements
4D. How light and sound interact with matter
4E. Atoms, nuclear decay, electronic structure, and atomic chemical behavior
Scientific inquiry and reasoning skill 2. Scientific reasoning and evidence-based problem solving
Scientific inquiry and reasoning skill 3. Reasoning about the design and execution of research
Scientific inquiry and reasoning skill 4. Data-based and statistical reasoning

[a] AAMC (2012).

would be perceived as less well prepared for medical school than those completing a more traditional curriculum. This has resulted in pressure on the undergraduate curriculum to expose students to an ever-growing body of factual information prescribed by medical school admissions requirements, sometimes at the expense of deep understanding of fundamental concepts. The overlay of rigid course prerequisites for premedical students has hampered faculty efforts to create interdisciplinary courses that reflect the strongly multidisciplinary approach of modern scientific inquiry. While there are a few isolated examples of integrated curricula (Bialek and Botstein, 2004; Ulsh *et al.*, 2009; Depelteau *et al.*, 2010; Gentile *et al.*, 2012), it has not become the norm in the way that was envisioned in the landmark *BIO2010* report (NRC, 2003).

At the same time, it has become apparent that premedical student education in its current form is not the optimal preparation for medical school (Emanuel, 2006; Gross *et al.*, 2008; Association of American Medical Colleges–Howard Hughes Medical Institute [AAMC-HHMI], 2009). This has spurred a critical re-examination of the knowledge and skills expected of entering medical students to identify the experiences, knowledge, and capabilities that allow students to become effective practitioners of science-based medicine. A committee of scientists, educators, and medical professionals was convened by the AAMC and the HHMI to make recommendations regarding educational objectives for premedical and medical students. Their report, *Scientific Foundations for Future Physicians* (*SFFP*; AAMC-HHMI, 2009), encouraged a shift from undergraduate curricula composed of a strict list of traditional science courses to curricula emphasizing a set of broad competencies that could be achieved with a more innovative, flexible approach.

The *SFFP* report's emphasis on competencies, skills, and deep understanding of fundamental concepts is informing an emerging conversation among medical schools on the extent to which current entrance requirements are sufficient to evaluate student preparation for medical training. While the Medical College Admissions Test (MCAT) remains a primary assessment for premedical student preparation, other measures beyond successful completion of traditional science course work (e.g., institutional competency evaluations, student portfolios) may serve as better indicators of student preparation. The *SFFP* report has also resonated with undergraduate educators in the life sciences. Indeed, these recommendations are analogous to those articulated in *Vision and Change in Undergraduate Biology Education: A Call to Action* (AAAS, 2011), a document that emerged from a series of national conversations, workshops, and conferences for life sciences educators.

The *SFFP* report was one of several sources of inspiration for the AAMC MR5 committee charged with shaping a revised MCAT exam that will take effect in 2015 (MCAT^{2015}). The MCAT is a rigorous, high-stakes test that, in combination with other application components, provides information on a student's preparation for medical school. The revised MCAT will test higher-order cognitive ability, placing greater weight on a student's ability to demonstrate skills and integrate knowledge across the natural, physical, and social sciences, as opposed to testing factual recall within well-defined disciplines. Student preparation will be assessed along two dimensions: understanding of basic, foundational concepts and the ability to demonstrate specific scientific inquiry and reasoning skills (AAMC, 2012). The MCAT^{2015} exam will be designed to test a student's performance at the intersection of these dimensions, for example, by asking them to use their understanding of fluid dynamics to understand the physiological implications of cardiovascular diseases such as atherosclerosis. The concepts and skills with particular relevance to physics instruction are shown in Table 1.

While the vision for interdisciplinary premedical and life sciences education may have crystallized, we are still a long way from realizing competency-based curriculum reform on a national scale. Even so, these imminent changes in the expectations for premedical students have stimulated a great deal of discussion among those involved in premedical advising and undergraduate curriculum development (Begley *et al.*, 2010; Presson and Thompson, 2011). The medical school admissions process is continuing to evolve in response to these anticipated changes in undergraduate curriculum and admissions testing, so we can expect these discussions to continue for the near term.

THE NATIONAL EXPERIMENT IN UNDERGRADUATE SCIENCE EDUCATION (NEXUS) COLLABORATION

The NEXUS project, funded by a 2010 HHMI Undergraduate Science Education grant, is a direct response to the *SFFP* report. For more than two decades, HHMI has supported initiatives that nurture future scientific researchers and science educators, as well as efforts that enhance science literacy among all citizens. To date, more than $900 million in

Table 2. NEXUS collaborating universities and their foci

Institution	Focus
UMCP	Linking the physical and biological sciences in the undergraduate biology curriculum: redesigning the undergraduate physics curriculum for the biological science student.
Purdue University	Development of an undergraduate chemistry curriculum and associated learning resources for the life sciences: redesigning undergraduate chemistry for the biological science student.
University of Maryland, Baltimore County (UMBC)	Experiments exploring the use of quantitative modeling core competency development in select foundational courses: the introduction of mathematical modeling in core undergraduate introductory biology courses for life sciences students.
University of Miami	Teaching and assessing the *Scientific Foundations for Future Physicians* competencies for entering medical students: the development of capstone case studies for integrating and assessing the competencies of biological science students.

competitive grants have been awarded to hundreds of colleges and universities in support of faculty-driven efforts to improve science education at the precollege, undergraduate, graduate, and medical school levels. HHMI's approach in science education reflects its philosophy of supporting "people, not projects," which allows faculty the creative freedom to pursue novel strategies for educational reform.

The four NEXUS universities have embarked on a collaboration to develop introductory undergraduate science curricula in a modular format that will address the *SFFP* competencies and be easily adaptable to a variety of institutional contexts. We are focusing on the introductory science courses that have been traditionally required for premedical students, which also form the core of most biological science curricula. Our strategy of developing a modular set of teaching materials, rather than wholly transdisciplinary courses, stems from our belief that educational innovations that can be woven into the existing curricular structures are more likely to be widely adopted. While each of our institutions has a different focus and approach to revising the introductory life sciences curriculum (Table 2), we are working together to develop shared strategies for designing and assessing competency-based curricula. In addition, modules developed at each site will be implemented at the other sites to assess their portability and efficacy across institutional contexts. Our intent is to establish the NEXUS project as an example of the power of collaborating across both disciplinary and institutional boundaries to effect curriculum reform.

As an integral part of the curriculum development process, the project is examining what it means to be competent, how competency can be measured, and how existing and planned curricula can be evaluated for their ability to help students achieve competency. The project is structured to facilitate communication across strategic goals and institutions. Leadership is provided by an executive steering committee and a global assessment committee that are composed of representatives from each of the four partner institutions. The executive steering committee holds monthly virtual meetings to establish overall project objectives, coordinate curriculum development activities, facilitate collaborative activities (e.g., adoption of teaching modules across multiple institutions), and develop dissemination strategies. The global assessment committee coordinates the identification and development of common assessment strategies among the participating institutions. An external advisory board composed of university science faculty, assessment experts, and individuals involved in drafting the new medical school recommendations provides guidance on all aspects of the project and serves as a link to the national biology and premedical education community. Once or twice each year, the entire group meets face-to-face to work out the details of development, assessment, and dissemination.

This collaborative structure allows the project to transcend the efforts of any single institution working in isolation. The foci of the four institutions are complementary, encompassing all of the introductory science subjects that form the traditional premedical curriculum. Although each institution is taking the lead on a specific aspect of curriculum development, each effort is designed to draw from the expertise of faculty at all four institutions. This is intended to ensure that the final modules are useful in multiple educational settings. In addition, when faculty members are actively engaged in developing instructional materials, they are more likely to use those materials in their teaching (Henderson and Dancy, 2008), so we expect our collaborative approach to facilitate cross-institutional module assessment and refinement.

An important part of the collaboration is increasing the capacity of faculty to contribute meaningfully to curriculum reform. Here again, the collaborative nature of the project is of great benefit. Each institutional team consists of faculty with expertise in the relevant science disciplines, faculty with experience in science education research, and assessment specialists. Among the collaborative activities that the group has organized is a series of workshops on active assessment (Hanauer *et al.*, 2009) guided by David Hanauer, who serves as a consultant to the project. These workshops have allowed each institution to develop a comprehensive assessment plan for its component of the overall project, with constructive feedback and input from partner institution faculty. The initial phases of assessment have focused on formative assessment and validation of newly developed tools, including one for mapping assessment questions to specific knowledge and competencies. Ultimately, these collaborative workshops will facilitate the creation of tools that can be used more generally to assess students' development of specific competencies.

INTEGRATING THE BIOLOGICAL AND PHYSICAL SCIENCES CURRICULA

All four NEXUS institutions are developing modules that interweave the biological and physical sciences to some extent, but we focus here primarily on the University of Maryland, College Park (UMCP), which is taking the lead on developing a prototype two-semester physics for life sciences sequence. The course teaches students the classical physical principles that lead to a deeper understanding of biological phenomena, including those needed to understand processes that occur at thermal energies and in liquids. Beyond providing a basic understanding of physical principles, the course focuses on the development of general scientific skills, including scientific modeling, problem solving, moving between multiple scientific representations, and experimental design. These approaches are traditionally emphasized in introductory physics courses but often receive less emphasis in biology courses, even though they have great utility across all scientific disciplines. A concerted effort is being made to build the course around topics and problems authentic to both biology and physics, to motivate students and help them understand the role of basic physics principles in biology (Watkins *et al.*, 2012). Ultimately, we seek to help students see the physical principles and constraints that affect living systems and understand their biological implications.

The curriculum development team consists of physicists, biologists, and science education researchers. It also draws upon the expertise of a wider pool of faculty members in biology, physics, chemistry, and math teaching the same population of students in upstream or downstream courses, who have provided insight into prerequisite course content and the physics conceptual knowledge necessary for success in upper-level biology courses. One of the most productive outcomes of these discussions has been the recognition of areas of overlap among introductory biology, chemistry, organic chemistry, and physics courses. The instructors of these courses have identified instances (e.g., the treatment of the concept of energy) in which disciplinary differences in conventions and terminology may lead to confusion on the part of students and are working together to ensure that students experience reinforcement across related courses rather than the perception that entirely new concepts are being presented. The specific content of the course has been the result of many months of negotiation between physics and biology faculty (for a firsthand account of this process, see Redish and Cooke, 2013).

The resultant course differs from most traditional introductory physics courses in prerequisites, content, and pedagogy. It requires students to have completed two semesters of calculus, one semester of introductory biology, and one semester of general chemistry. This allows us to more fully integrate students' prior scientific knowledge into their learning of physics, which will facilitate their development of interdisciplinary fluency. Rather than being a watered-down version of physics courses developed for engineers, the new course excludes topics that have limited relevance to biology (e.g., projectile motion, inclined planes, rotational motion) in favor of those more critical to an understanding of life processes (e.g., fluid dynamics; diffusion; dissipative forces; thermodynamics, including chemical energy).

In terms of pedagogy, the course follows a student-centered, active-engagement model that is the culmination of decades of research into the how students learn physics (Redish and Hammer, 2009). Before each class meeting, students complete brief background readings and write essay responses or pose follow-up questions via an online homework system. Responses are reviewed by the instructor and used to shape each class meeting's activities (Just in Time Teaching; Novak *et al.*, 1999). The majority of in-class time is taken up by demonstrations, conceptual clicker questions (following Eric Mazur's peer instruction model [Mazur, 1997]), and problem-solving activities in which students work out solutions collaboratively using whiteboards. Extensive use is made of instructional technology, including simulations (e.g., PhET [Wieman *et al.*, 2008]), videos, and data analysis tools (e.g., ImageJ). In the accompanying laboratory, students carry out statistical physics experiments using a 40× projection microscope and video analysis software to analyze the movement of plastic microspheres within microfluidic cells. Collectively, these activities encourage students to develop analytical and problem-solving skills, rather than rely on rote memorization. While we have chosen to create a single coherent course, the materials are being developed in a modular format that is organized into "threads" (e.g., mathematical modeling, energy and chemical bonds, action potentials). Adopters can use individual instructional resources (e.g., readings, clicker questions, homework problems) or insert an entire thread into their existing courses. All resources have been developed and organized using an open-source format (wiki) that will enable the resources to grow and evolve in response to the changing scientific and instructional landscape. Although the process of fine-tuning the curriculum is still underway, current versions of instructional and assessment resources can be found at http://NEXUSphysics.umd.edu.

Instructional materials and assessments have been specifically designed to support competence building. This has involved identifying the measurable subcomponents that constitute a competency (Table 3) and then designing the learning tasks to allow students to develop each competency over the two-semester course sequence. While the process of measuring learning outcomes requires that these skills be specified precisely, we recognize that our goals for students go beyond simple recognition to encompass cognitively demanding tasks, such as being able to integrate discrete ideas into more complex schemas and being able to draw appropriately from different kinds of problem-solving approaches, depending on the context. Thus, the competencies can be envisioned as multiple strands that run through the curriculum. The intersection of multiple strands is embodied in individual learning tasks (e.g., homework problems, group work, clicker questions) that simultaneously address more than one competency. These learning tasks allow students repeated opportunities to build competencies in differing combinations and contexts. In measuring student progress in building competencies, we are using an array of qualitative and quantitative approaches to provide a multidimensional representation of student learning, as recommended by the NRC (2012).

We are fine-tuning the course content via an iterative process (Figure 1). As learning tasks are developed, they are mapped to specific *SFFP* competencies and competency subcomponents. Tasks then undergo a rigorous process of analysis to ensure they foster development of the specified competencies; this is done by using a rubric that measures the degree to which the tasks integrate knowledge and reasoning strategies across disciplinary boundaries (Svoboda Gouvea *et al.*, 2013). To provide formative assessment data, we are videotaping class meetings and recitation sessions in which students work in groups to solve complex problems. We are also using structured interviews and qualitative analysis of

Table 3. Example of identification of measurable subcomponents that constitute a competency, in this case applying quantitative reasoning and appropriate mathematics to describe or explain phenomena in the natural world[a]

Multirepresentational competency is a component of quantitative reasoning that involves the ability to reason about complex phenomena using a variety of different modalities, such as diagrams, equations, graphs, and verbal descriptions. To demonstrate multirepresentational competency, a student should be able to:

1. Create a graph of various physical variables as a function of time or space from a description of a physical phenomenon and be able to describe what is happening physically from a graph.
2. Create the graph of the derivative of a variable from the graph of that variable and vice versa.
3. Look at an equation and be able to describe in words what it means for a physical system.
4. See the value of drawing a figure or diagram for the understanding of a physical situation or for solving a problem.
5. Decide which factors are relevant to include in a diagram and which are superfluous (cartooning).

[a] *SFFP* competency E1 and MCAT^{2015} scientific inquiry and reasoning skill 1.

student artifacts (e.g., homework, exams, worksheets). This ethnographic approach provides insight into how students perceive and respond to specific learning tasks. A detailed example of this process, focusing on student understanding of where energy comes from in an exothermic chemical reaction, can be found in Dreyfus *et al.* (2013). Based on task analysis and formative assessment data, the learning tasks are revised to increase their relevance, effectiveness, and authenticity.

Summative assessments of course impact have three foci. First, we are measuring the effect of the course on the degree to which students embrace interdisciplinary thinking (e.g., concepts and strategies traditionally used in one scientific discipline have relevance in other disciplines). Student attitudes are being assessed with the Maryland Physics Expectations II survey (Redish *et al.*, 1998), a well-validated instrument that has been modified to include a set of questions (referred to as the interdisciplinary cluster) that specifically probes whether students feel interdisciplinary approaches are a valuable problem-solving tool for the biological sciences. Second, we want to ensure that our attempts to make the physics course more accessible and relevant to biology students have not jeopardized their understanding of physics. This is being assessed with established tools, including the Force-Motion Concept Evaluation and the electricity components of the Conceptual Survey of Electricity and Magnetism and Brief Electricity and Magnetism Assessment. Third, we want the students to develop competency in applying physical principles and quantitative reasoning to solving biochemical, biological, and biomedical problems. Measuring this complex interplay of skills and knowledge requires a multifaceted approach, so we are using a combination of quantitative and qualitative methods. These include multiple-choice questions that subsequently ask students to describe the reasoning behind their choice of answers, complex homework problems, and essay-format exam questions. These assessment tasks have been developed using the framework established by Edward F. (Joe) Redish and colleagues during 15 yr of previous research into students' epistemological development in the context of a traditional, algebra-based physics course (Redish, 2003; Redish and Hammer, 2009). We have categorized these assessment tasks according to the competencies addressed and are analyzing them at several points in the course to document competency development. Ultimately, this will enable us to develop standardized instruments and accompanying rubrics that can be used to assess student mastery of key competencies identified in the *SFFP* and related reports.

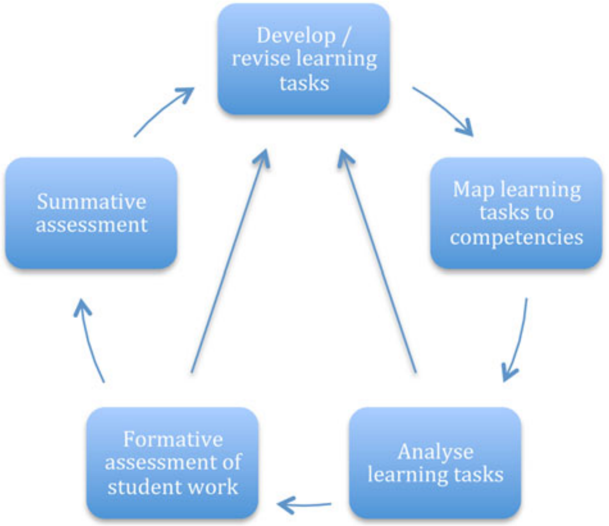
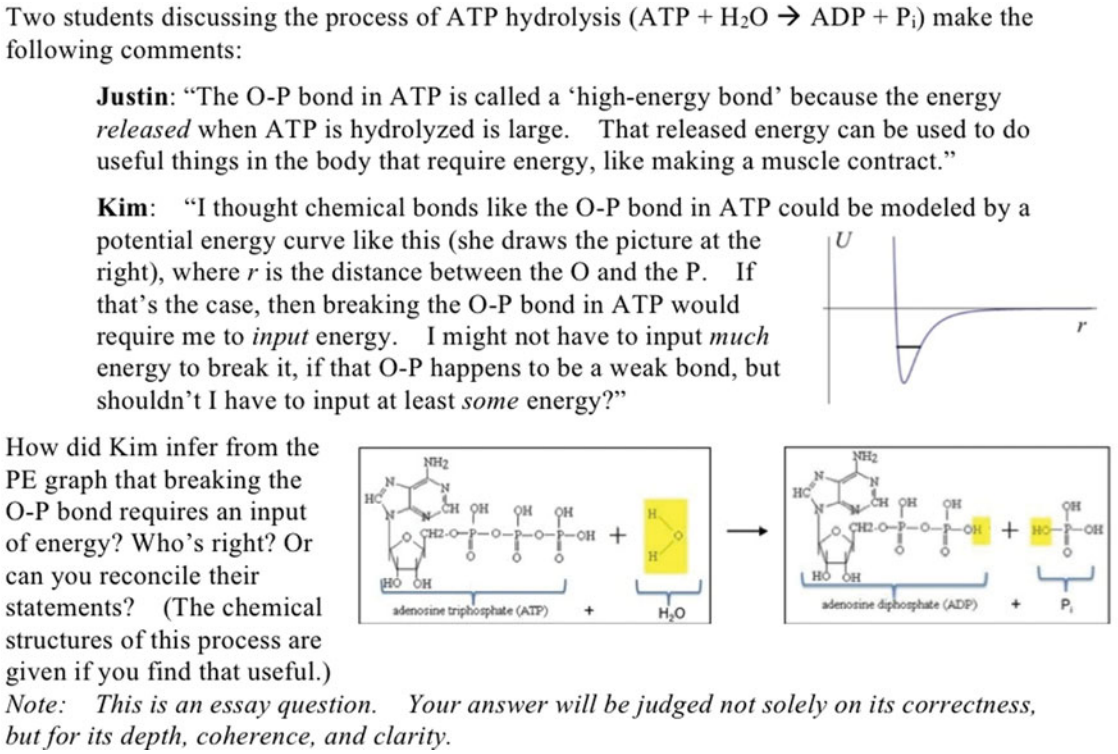


Figure 1. The iterative process of learning task development, analysis, and assessment.

We present here an example of this summative assessment process. Students were presented with an exam question that asked them to make inferences about the biological process of ATP hydrolysis based on a potential energy diagram (Figure 2). This question required students to demonstrate *SFFP* competencies E1 (applying quantitative reasoning and appropriate mathematics to describe or explain phenomena in the natural world) and E3 (demonstrating knowledge of basic physical principles and their applications to the understanding of living systems). Student responses to this essay question were evaluated with a multidimensional rubric that measured the extent to which each student demonstrated the competencies of interest. For example, one dimension of the rubric for the ATP exam question was multirepresentational competency (Table 3). Student responses were scored on a scale of 0–2, with 2 indicating the student's verbal description correctly identified the *x*-axis of the potential energy diagram as indicating the potential energy of a pair of atoms and the *y*-axis as indicating the distance between them. A student response that contained only one of these two explanations received a score of 1, and a response that contained neither received a score of 0. The proportion of students demonstrating multirepresentational competency



Two students discussing the process of ATP hydrolysis ($ATP + H_2O \rightarrow ADP + P_i$) make the following comments:

> **Justin**: "The O-P bond in ATP is called a 'high-energy bond' because the energy *released* when ATP is hydrolyzed is large. That released energy can be used to do useful things in the body that require energy, like making a muscle contract."
>
> **Kim**: "I thought chemical bonds like the O-P bond in ATP could be modeled by a potential energy curve like this (she draws the picture at the right), where *r* is the distance between the O and the P. If that's the case, then breaking the O-P bond in ATP would require me to *input* energy. I might not have to input *much* energy to break it, if that O-P happens to be a weak bond, but shouldn't I have to input at least *some* energy?"

How did Kim infer from the PE graph that breaking the O-P bond requires an input of energy? Who's right? Or can you reconcile their statements? (The chemical structures of this process are given if you find that useful.)

Note: This is an essay question. Your answer will be judged not solely on its correctness, but for its depth, coherence, and clarity.

Figure 2. Summative assessment question designed to reveal student competency with applying quantitative reasoning and physical principles to understand living systems.

(i.e., a score of 2) on this question can be compared with the proportion demonstrating multirepresentational competency on earlier tasks as an indicator of the degree to which the curriculum helps students attain this competency. Weaknesses in the curriculum revealed through this process trigger another cycle of task revision and analysis (Figure 1).

The course was piloted during the 2011–2012 academic year in a small class (~20 students) format taught by a single, experienced instructor (Joe Redish). It is being offered again during the 2012–2013 academic year with approximately double the number of students in two separate sections taught by two different instructors. We have also begun seeking feedback and engagement from physics faculty at other institutions as a way of broadening the pool of instructors, while retaining a class size that permits intensive formative assessment. In 2013–2014, the course will be scaled up to serve 300 students per semester in lectures sections of 150 students each. Our challenge in scaling up the size of the course will be to preserve the interactivity that now characterizes the small pilot classes. One essential element of this interactivity is group work. Over the near term, this may be difficult in the currently used theater-style lecture halls, but we will soon break ground on a new instructional building that will house large-capacity lecture halls with pivoting seating that allows students to move from a traditional, forward-facing configuration to one that allows them to gather in small groups around tables.

Over the remaining 2 yr of the project, our goal is to build a cadre of physics instructors who are committed to replicating the interdisciplinary, active-engagement approach of the new course. The first step in this process was to convene a workshop in January 2012, bringing together physicists and biologists representing the four NEXUS institutions, as well as those from other institutions who have been involved in similar efforts. The discussions focused on existing teaching resources and the extent to which our current curricula reflect interdisciplinary, competence-based educational approaches. In the short term, this has increased awareness among the participants of teaching resources that are already in existence, including some that have served as the basis for new activities being piloted in the NEXUS project. In the long term, we hope that participants will engage in a critical review of the extent to which their existing physics for life sciences curricula support competency building and subsequently adopt NEXUS curriculum modules designed to bolster those competencies.

In addition to UMCP's efforts to create a new physics for life sciences course sequence, the other NEXUS institutions are also developing instructional modules for introductory biology and chemistry courses, some of which will require biology students to integrate the physical and biological sciences. Each module will consist of several standardized elements, including 1) learning objectives, 2) specific competencies addressed, 3) student activities (e.g., readings, exercises, problem sets), 4) answer keys, 5) instructor implementation guidelines, and 6) assessment guidelines. For example, the University of Maryland, Baltimore County (UMBC), is taking the lead on developing inquiry-based learning modules for introductory biology courses that train students to apply quantitative reasoning and mathematical modeling to explain biological phenomena. While this effort focuses on enhancing the competency of introductory biology students in the use of quantitative reasoning, the goal is to design modules that interweave the major principles of physics, chemistry, and biology. When fully developed in 2014, modules and assessment instruments resulting from the NEXUS project will be made freely available to institutions nationwide via the project website (www.hhmi.org/grants/office/nexus).

DEVELOPING A SHARED VISION FOR CURRICULUM REFORM

Undergraduate science education reform has a long history of disjunct, solitary efforts that are neither sustainable nor replicable outside their original contexts. The theoretical framework for educational reform typically follows Rogers' (1962) model of diffusion of innovations, in which faculty become aware of curricular innovations and subsequently adopt them without much modification. However, recent studies of instructional practices in physics indicate that faculty expect to be meaningfully involved in adapting existing teaching methods and creating new ones (Henderson and Dancy, 2008). Through a review of nearly 200 recently published undergraduate science education journal articles, Henderson *et al.* (2010, 2011) identified four categories of change strategies. Current practices are dominated by "disseminating curriculum/pedagogy" and "developing reflective teachers," which operate at the level of the individual faculty member. A less widely seen approach, yet one that holds great promise for achieving sustainable change on a broad scale, is "developing shared vision." This change strategy is aimed at the level of the department, institution, or disciplinary community, and involves groups of individuals working together to set goals and identify changes required for educational reform. It is this communal approach that characterizes the NEXUS project.

There are many challenges to a project of this scale. Although all participating institutions are research-extensive universities, each varies with respect to institutional culture, traditions, and educational priorities. This has required a complicated system of communication that involves wikis (for collaborative authoring and critiquing), online project-management systems (for setting goals and deadlines, as well as sharing documents), regular conference calls (for sharing progress and strategic planning), and periodic face-to-face meetings (for cultivating a sense of community). It has involved working to develop a common understanding, both between faculty within different scientific disciplines and between science researchers and educators. We have also learned to temper our ambitions regarding the scale and pace of our reform efforts—thoughtful, sustainable change takes time and effort.

In its short history, the NEXUS project has inspired cross-disciplinary conversations, engaged dozens of scientists in science education research, and facilitated a new approach to curriculum reform that focuses on the common goal of developing scientific competencies. These outcomes have been greatly enriched by the participation of faculty from different institutions, who bring different perspectives and experience. Working collaboratively, we can achieve something that we could not achieve by working alone (Cox, 2004). The collaboration has also highlighted some of the challenges associated with disseminating teaching innovations beyond their point of origin, an outcome that is essential to achieving broader science education reform. As we work through these challenges, we seek to create a road map for other institutions that aspire to implement the vision advocated in the *SFFP* and *Vision and Change* reports.

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