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Essay

Biology and Physics Competencies for Pre-Health and Other Life Sciences Students

Robert C. Hilborn* and Michael J. Friedlander†

*American Association of Physics Teachers, College Park, MD 20740; †Virginia Tech Carilion Research Institute and School of Medicine, Roanoke, VA 24016

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The recent report on the *Scientific Foundations for Future Physicians* (*SFFP*) and the revised Medical College Admissions Test (MCAT) reframe the preparation for medical school (and other health professional schools) in terms of competencies: what students should know and be able to do with that knowledge, with a strong emphasis on scientific inquiry and research skills. In this article, we will describe the thinking that went into the *SFFP* report and what it says about scientific and quantitative reasoning, focusing on biology and physics and the overlap between those fields. We then discuss how the *SFFP* report set the stage for the discussion of the recommendations for the revised MCAT, which will be implemented in 2015, again focusing the discussion on biology and physics. Based on that framework, we discuss the implications for undergraduate biology and physics education if students are to be prepared to demonstrate these competencies.

INTRODUCTION AND BACKGROUND

In February 2012, the Association of American Medical Colleges (AAMC) announced the revision of the Medical College Admission Test (MCAT), the result of a multiyear process that began with the development of the report *Scientific Foundations for Future Physicians* (*SFFP*; AAMC–Howard Hughes Medical Institute [HHMI] Joint Committee, 2009). The *SFFP* report, produced as a joint effort of AAMC and the HHMI, focused on the natural sciences and quantitative "competencies" needed for the preparation of successful future physicians. The report included recommendations both for undergraduate preparation in the natural sciences and mathematics for medical school and for medical education itself.

The *SFFP* report explicitly framed its arguments in terms of what knowledge and skills students should acquire in the natural sciences and mathematics and what they should be able to do with that knowledge and those skills—in short, the competencies that students should be prepared to demonstrate if they are to be successful physicians. An analogous report on competencies in the social and behavioral sciences was written a few years later (Association of American Medical Colleges, 2011a).

The focus on competencies as a method of articulating student preparation was implemented intentionally. The competency formulation is much more explicit than a simple list of courses in explaining what students should know and be able to do. For example, a year of organic chemistry, though there is a general consensus of what that means, still might cover a multitude of different topics—only a few of which might be essential for future physicians. Thus, a competency formulation provides guidance to both undergraduate faculty and students about what is important in preparing for health sciences careers.

Another important consideration is that many undergraduate faculty members feel that the rigid course requirements for medical school admissions and the list of topics covered on the MCAT constrain their abilities to develop innovative ways to educate future physicians and other students preparing for science, technology, engineering, and mathematics careers (National Research Council, 2003). Traditionally, medical schools require applicants to take a year of general chemistry, a year of organic chemistry, a year of physics, and a year of biology. Additional course requirements in English and mathematics are common. Those course requirements do not specify what should be taught in those courses. So, moving to a competency model for medical school admissions would

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Address correspondence to: Robert C. Hilborn (rhilborn@aapt.org).

provide both specificity and flexibility in how undergraduate faculty provide curricula that help students attain the competencies.

The *SFFP* and MCAT are far from being pioneers in the use of competencies to express learning objectives. In engineering, the Accreditation Board for Engineering and Technology accreditation program (ABET, 2009) moved to a competency model in 2000. More recently, the report *Vision and Change in Undergraduate Biology Education* (American Association for the Advancement of Science, 2011) articulated the objectives for undergraduate biology majors in terms of competencies. In medical education itself, the U.S. Medical Licensing Exam has moved to a competency model by asking examinees to use their medical science knowledge to integrate information across disciplines and reason about medical problems rather than simply regurgitate facts. In K–12 education, the recently released *Framework for K–12 STEM Education* (National Research Council, 2012) and the draft of the *Next Generation Science Standards* (www.nextgenscience.org) explicitly link scientific content knowledge with science and engineering practices, which call upon students to demonstrate the ability to use the content knowledge in a variety of ways.

In a more general education framework, a 2002 National Center for Educational Statistics report, *Defining and Assessing Learning: Exploring Competency-Based Initiatives* (Jones *et al.*, 2002, p. vii), defines a competency as "a combination of skills, abilities, and knowledge needed to perform a specific task." The report defines competency-based initiatives in the following way:

> Competency based initiatives, then, are those purposeful actions undertaken by postsecondary institutions directed at defining, teaching, and assessing competencies across their system. (p. vii)

The report goes on to describe methods that help students become competent. "Competencies are the result of integrative learning experiences in which skills, abilities, and knowledge interact to form bundles that have currency in relation to the task for which they are assembled" (Jones *et al.*, 2002, p. 7).

THE *SFFP* REPORT

Let us now turn to the details of the *SFFP* report and its recommendations for competencies. The report (AAMC–HHMI Joint Committee, 2009) articulates for future physicians competencies they should achieve in their undergraduate preparation for medical school and what should be accomplished as part of their medical school education. Moreover, the *SFFP* report made the case that the undergraduate competencies would also provide a solid preparation for those students who may choose to pursue other health professions or advanced education and training in other fields, including the physical, biological, or social sciences. In this paper, we focus on the undergraduate preparation.

The *SFFP* report formulates its recommendations for premedical preparation in terms of eight competencies. Each competency is accompanied by a set of six to eight learning objectives that flesh out the competency. In turn, each learning objective has a series of examples to illustrate the scope and level of sophistication the SFFP Committee had in mind for that learning objective. The examples are not intended to indicate specific required content nor do they exhaust the possibilities for that learning objective, but are intended solely to be instructive as exemplars.

The first two SFFP competencies focus on scientific inquiry and reasoning skills, which cut across the scientific disciplines. We list here those first two competencies and one learning objective for each of them. Each learning objective is accompanied by one of the examples from the *SFFP* report.

Competency E1

> Apply quantitative reasoning and appropriate mathematics to describe or explain phenomena in the natural world.
>
> Learning Objective 1. Demonstrate quantitative numeracy and facility with the language of mathematics.
>
> Example: Express and analyze natural phenomena in quantitative terms that include an understanding of the natural prevalence of logarithmic/exponential relationships (e.g., rates of change, pH).

Competency E2

> Demonstrate understanding of the process of scientific inquiry, and explain how scientific knowledge is discovered and validated.
>
> Learning Objective 4. Be able to articulate (in guided inquiry or in project-based research) scientific questions and hypotheses, design experiments, acquire data, perform data analysis, and present results.
>
> Example: Be able to develop a project plan and report: generate a hypothesis, design a protocol with appropriate controls, consider control of relevant variables, collect and analyze quantitative data, draw conclusions, and present the results (e.g., as a scientific seminar, paper, or poster).

Note that these first two SFFP competencies are quite broad. The examples indicate that these competencies can be gained through the kind of laboratory work associated with the typical introductory biology, chemistry, and physics courses. A specialized course in research methods, for example, is not needed, although courses in any of the sciences that incorporate research methods are encouraged.

We now turn to the natural sciences competencies associated with physics and biology. Again, we state the competency and give one of the learning objectives associated with that competency and an example of the relevant topics. We start with the competency that is most closely related to topics taught in the traditional introductory physics course.

Competency E3

> Demonstrate knowledge of basic physical principles and their applications to the understanding of living systems.
>
> Learning Objective 1: Demonstrate understanding of mechanics as applied to human and diagnostic systems.

> Example: Apply knowledge of centripetal acceleration to "g-force" devices used to train jet pilots and astronauts.

We note that the competency is quite broad, but focuses attention on those principles most directly related to understanding the behavior of living systems. Similarly, the learning objective dealing with mechanics—the study of motion and forces—directs us to those aspects of mechanics that help us understand the components of the human body at multiple scales and diagnostic systems used in many aspects of life and health sciences, such as centrifuges. The *SFFP* report recognizes that other aspects of mechanics, such as energy and torque, may be important in developing the concepts needed to apply mechanics to living systems, but the competency to be developed for life sciences students focuses on applications to living systems.

Not surprisingly, four of the SFFP recommended competencies focus on biochemistry and biology. Again, we list the competencies. For two of them, we provide learning objectives and examples that show the close ties between the contemporary approach to biology and physics.

Competency E5

> Demonstrate knowledge of how biomolecules contribute to the structure and function of cells.

Competency E6

> Apply understanding of principles of how molecular and cell assemblies, organs, and organisms develop structure and carry out function.
>
> Learning Objective 1: Employ knowledge of the general components of prokaryotic and eukaryotic cells, such as molecular, microscopic, macroscopic, and three-dimensional structure, to explain how different components contribute to cellular and organismal function.
>
> Learning Objective 4: Demonstrate knowledge of the principles of biomechanics and explain structural and functional properties of tissues and organisms.

Examples:

- Apply understanding of force and torque to explain why small differences in muscle insertion position make a significant difference in the speed and force created by limb movement.
- Explain the energetics and role of motor proteins in contraction and cellular movement.
- Explain the physics of how blood movement and pressure are affected by vessel diameter.

Competency E7

> Explain how organisms sense and control their internal environment and how they respond to external change.
>
> Learning Objective 2: Explain physical and chemical mechanisms used for transduction of various forms of energy into bioelectrical signals in cells and networks of cells and information processing in the sensing and integration of internal and environmental signals.
>
> Example: Explain how ion channel permeability is altered by physical or chemical stimuli and how this contributes to electrical signaling within and between cells.

Competency E8

> Demonstrate an understanding of how the organizing principle of evolution by natural selection explains the diversity of life on earth.

Although the *SFFP* competencies were developed for recommendations for preparation of future physicians, we argue that they provide an excellent framework for preparing undergraduate students for a wide range of careers in the health and natural sciences. Those competencies are in no respects narrowly premedical.

THE REVISED MCAT

To show how a competency model informs the natural sciences content of the revised MCAT, we need first to describe the changes that AAMC is implementing. At a structural level, the revised MCAT will consist of four sections (Association of American Medical Colleges, 2011b):

1. Biological and Biochemical Foundations of Living Systems
2. Chemical and Physical Foundations of Biological Systems
3. Psychological, Social, and Biological Foundations of Behavior
4. Critical Analysis and Reasoning Skills

New to the revised MCAT is the section on the psychological, social, and biological foundations of behavior. This new material recognizes that, in many cases, the social and behavioral components of health and disease are just as important as the physical, chemical, and biological components and that they are indeed intimately linked to those processes.

The critical analysis and reasoning skills section is a direct replacement of the current verbal reasoning section and will ask the students to read and answer questions about passages from the humanities and social and behavioral sciences. All the information needed to answer the questions will be provided in the passage. The key motivation of this section is to evaluate the student's competency in analyzing information that is newly presented and in using a variety of cognitive skills and analytical tools to make sense of the information and integrate it into a useful construct.

The revised MCAT will have more biochemistry and cell and molecular biology than does the current exam. The biochemistry will be limited to that covered in a one-semester foundational course, as recommended by the American Chemical Society's guidelines for undergraduate chemistry programs (American Chemical Society, 2008). The cell and molecular biology concepts will be at the level taught in many introductory biology courses across the country. These changes were made in recognition of the growing importance of knowledge at the biochemical and cell and molecular biological levels for developing a truly mechanistic understanding of health and disease in the practice of medicine.

The biological, chemical, and physical parts of the revised exam will be built around five foundation concepts that play the role of the competencies laid out in the *SFFP* report.

Those five foundational concepts are (Association of American Medical Colleges, 2011b, pp. 10–11):

> 1. Biomolecules have unique properties that determine how they contribute to the structure and function of cells and how they participate in the processes necessary to maintain life.
>
> 2. Highly-organized assemblies of molecules, cells, and organs interact to carry out the functions of living organisms.
>
> 3. Complex systems of tissues and organs sense the internal and external environments of multicellular organisms and, through integrated functioning, maintain a stable internal environment within an ever-changing external environment.
>
> 4. Complex living organisms transport materials, sense their environment, process signals, and respond to changes using processes understood in terms of physical principles.
>
> 5. The principles that govern chemical interactions and reactions form the basis for a broader understanding of the molecular dynamics of living systems.

Each foundational concept is supported by a list of appropriate content topics, which we will not describe here. (As mentioned previously, in the *SFFP* report, there is an intermediate layer of learning objectives associated with each competency. The *SFFP* report intentionally avoided listing specific, detailed content topics.) The list of "allowed" MCAT content topics was generated by having current MCAT science topics rated by medical students, medical school basic science faculty, and residents and correlating those topic rankings with what undergraduate faculty report is commonly taught. The content topic lists and the details of the selection process are available through the AAMC website (www.aamc.org/initiatives/mr5).

In addition to science content topics, the MCAT will test scientific inquiry and reasoning skills (SIRS):

1. Knowledge of scientific concepts and principles
2. Scientific reasoning and evidence-based problem solving
3. Reasoning about the design and execution of research
4. Data-based and statistical reasoning

Note that the quantitative skills focus on reasoning about data using statistics and other mathematical tools. These skills are just those that are taught—sometimes implicitly rather than explicitly—in the laboratory components of most introductory college and university science courses. In alignment with the *SFFP* report, the MCAT does not expect that students will need to take courses specifically in research methods.

Scientific inquiry and quantitative reasoning skills will not be tested in isolation in the revised MCAT. Students' competencies in the natural sciences and quantitative reasoning will be tested by essay questions that ask students to apply one or more of the SIRS skills and their content knowledge to answer questions about passages that describe scientific problems in the context of living systems.

IMPLICATIONS FOR UNDERGRADUATE EDUCATION

How will undergraduate institutions help students who are interested in medical careers develop the competencies recommended by the *SFFP* report and those that will be tested on the MCAT? As a first approximation, undergraduate faculty need not do much more than make sure that students have experience using the scientific inquiry and reasoning skills described above to solve scientific problems. In addition, chemistry and physics faculty should give students practice in applying the concepts of chemistry and physics to situations that apply to the understanding of living systems. Education research has shown (Bransford *et al.*, 1999) that students have difficulty applying what they have learned in contexts different from the context in which the material was first learned. Of course, this transfer of learning is something we want our students to master, so having them practice applying their knowledge and scientific reasoning skills in a wide variety of areas is a virtue in its own right.

Competencies have the advantage, compared with standard course requirements, of providing much-needed specificities for desired learning outcomes. A year-long course in physics, for example, might focus on Einstein's theory of relativity and elementary particle physics, topics that are exciting and intellectually satisfying but only remotely related to the physics knowledge and skills that are needed by future physicians. Spelling out the competencies tells the students what they should be learning and the faculty members what they should be teaching for the students with specific career aspirations. Moreover, faculty members can develop assessments that target specific student competencies.

The SFFP competencies should also be useful for college and university faculty members who need to write course learning objectives to meet the demands of regional accrediting associations. Once those learning objectives are in place, it is much easier to develop assessments of student learning (Hanauer and Bauerle, 2012) also required by accrediting associations.

As mentioned previously, the focus on competencies allows colleges and universities to think about creative curriculum innovations, such as integrated science courses and nonstandard sequences of courses. We believe that such flexibility might be one of the most important results of adopting a competency model. SFFP undergraduate competencies, though focused on future physicians, are broadly applicable for all pre-health students and, in the opinion of the authors, should be part of the education of all science students.

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