Creating an Interdisciplinary Introductory Chemistry Course *without* Time-Intensive Curriculum Changes

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Cutting edge scientific research increasingly occurs at the interface of disciplines, and equipping students to recognize interdisciplinary connections is essential for preparing the next generation of researchers, health workers, and policymakers to solve the toughest scientific problems (*1, 2*). Accordingly, new recommendations for premedical curricula issued by the American Association of Medical Colleges (AAMC) and the Howard Hughes Medical Institute (HHMI) call for a competency-based training, shifting away from specific course requirements to the ability of students to apply knowledge and recognize underlying scientific principles in medicine (*3*). Chemical principles underlie all of the life sciences, and while the relevance of chemistry to biological processes is frequently discussed in advanced chemistry courses, this is long after most general chemistry and premedical students have stopped taking chemistry entirely. Introductory chemistry courses therefore provide a unique opportunity to impact a diverse cross section of students (*4*). Additionally, early exposure to the applications of chemistry may be particularly relevant for the recruitment of underrepresented minorities and students from lower socioeconomic backgrounds into the sciences, since research indicates that students from lower economic backgrounds value college majors with clear career applications (*5*).

Some schools have implemented combined introductory chemistry/biology courses, which can offer valuable learning experiences but require ongoing commitments from dedicated faculty members and curriculum flexibility (*6, 7*). More commonly, schools have rigid curriculum guidelines in general chemistry, which are not amenable to redesigning the course. For example, in colleges that condense general chemistry into a single semester or in high school courses with state- or AP-based syllabi, removing topics from the curriculum to make room for interdisciplinary units is not an option. Ideally, an introductory chemistry course should inspire and equip students to recognize underlying chemical principles in other disciplines and solve interdisciplinary problems *without* sacrificing the original content in the course.

Here we describe the development, implementation, and assessment of succinct examples from biology and medicine that illuminate applications of chemical principles. These examples were incorporated into the lectures and problem sets of the 2007 and 2008 semesters of the general chemistry course 5.111 at MIT, with a yearly fall enrollment of >200 freshman from 19 different intended academic majors, including over 60% women and 25% underrepresented minority students (see Supplementary Table 1). The materials are freely available to other educators and the

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TABLE 1. **General chemistry lecture topics and corresponding in-class biology and medicine-related examples**[a]

Chemistry lecture topics	Biology-related examples
Introduction and course overview	• Chemical principles in research at MIT
Wave-particle duality of light and matter	• Quantum dot research at MIT
Periodic trends	• Atomic size: sodium ion channels in neurons
Covalent bonds, Lewis structures	• Cyanide ion in cassava plants, cigarettes
	• Thionyl chloride for the synthesis of novacaine
Exceptions to Lewis structure rules	• Free radicals in biology: role in DNA damage *and* essential for life
	• Nitric oxide (NO) in vasodilation (and Viagra)
Polar covalent bonds, ionic bonds	• Water-soluble versus fat-soluble vitamins: comparing folic acid and vitamin A
VSEPR theory	• Molecular shape in enzyme−substrate complexes
Valence bond theory and hybridization	• Restriction of rotation around double bonds: application to drug design
	• Hybridization example: ascorbic acid (vitamin C)
Determining hybridization in complex molecules	• Identifying molecules that follow the "morphine rule"
Thermodynamics	• Glucose oxidation: harnessing energy from plants
Free energy and control of spontaneity	• ATP-coupled reactions in biology
	• Thermodynamics of H-bonding: DNA replication
Chemical equilibrium, Le Chatelier's principle	• Maximizing the yield of nitrogen fixation: inspiration from bacteria
	• Le Chatelier's principle and blood-oxygen levels
Acid−base equilibrium, bufferes, and titrations	• pH and blood: effects from vitamin B_{12} deficiency
Balancing redox equations, electrochemical cells	• Oxidative metabolism of drugs
Oxidation/reduction reactions	• Reduction of vitamin B_{12} in the body
Transition metals	• Metal chelation in the treatment of lead poisoning
	• Geometric isomers and the anticancer drug cisplatin
Crystal field theory, metals in biology	• Inspiration from metalloenzymes for the reduction of greenhouse gases
Rate laws	• Kinetics of glucose oxidation in the body
Nuclear chemistry and elementary reactions	• Medical applications of radioactive decay (^{99}Tc)
Reaction mechanism	• Reaction mechanism of ozone decomposition
Enzyme catalysis	• Enzymes as the catalysts of life, inhibitors as drugs
Biochemistry	• The methionine synthase case study

[a]The examples and homework problems (not listed) are available online (*8*).

public via MIT OpenCourseWare (OCW) and are a straightforward way to apply the new AAMC-HHMI recommendations for more integrative courses to any general chemistry curriculum.

Overview of Biology- and Medicine-Related Examples in Freshman Chemistry. On the basis of conversations with students and course evaluation responses from past years, it was observed that MIT freshman enrolled in the nonadvanced version of general chemistry were very interested in human health and biology, but that many of those same students viewed chemistry as uninteresting or irrelevant to their interests. To address this disconnect while keeping the rigorous chemistry curriculum intact, we began supplementing lectures and homework with brief examples from biology and medicine.

Examples ranging from 2 to 5 min were incorporated into lectures, such that the 36-lecture course now includes approximately 30 in-class biology-related examples. A summary of course lecture topics and corresponding interdisciplinary examples can be found in Table 1. In many cases, examples serve to stress the significance or potential applications of a given topic. For instance, when introducing periodic trends, the selectivity of ion channels in neurons is used to illustrate the importance of atomic radius in proper neuron signaling, helping to answer the question "Why should we care about periodic trends?". Still other examples introduce the class to the types of problems they could someday tackle using chemistry. In a kinetics lecture, for example, students are introduced to HIV protease inhibitors and the use of kinetic measurements to analyze drug candidates.

For other course topics, a problem-solving example within the lecture is directly replaced with a relevant biology-applied problem. For instance, in the introduction of the Nernst equation for redox reactions, the in-class problem was changed to address the reduction of vitamin B_{12} in the body. In another lecture, students apply their knowledge of polar covalent bonds to predict which vitamins are water-soluble and easily excreted and which are fat-soluble and can build up to dangerous levels. The use of classroom response devises, or clickers, further facilitates student participation for in-class problem solving examples.

To reinforce the interdisciplinary connections formed in lecture, we include several biology-related problems in each of the weekly problem sets. Students often gauge how important a concept is by its presence or absence on homework and exams. The biology-related homework problems require students to use their chemical problem solving skills and stress that interdisciplinary thinking is part of the class, not an aside that "doesn't count". Some of these problems require students to apply chemical knowledge to draw conclusions about a biological system. For example, using Lewis structure rules for free radicals, students

predict which byproducts of metabolism are highly reactive radical species. In other problems, the biology or medicine connection is simply a framework for the chemistry problem, such as identifying the potential hydrogen bond donor and acceptor atoms in a cancer drug.

Implementation, Assessment, and Outcome. Implementation of the in-class and homework examples from biology and medicine occurred stepwise over two years, as the material was developed. In the fall of 2007, examples were included throughout the second half of the course (lectures 19−36), and in the fall of 2008, the examples were throughout the entire course (lectures 1−36). An assessment of the curriculum innovations in these semesters was conducted by the Teaching and Learning Laboratory (TLL) at MIT, and 343 student subjects, 79% and 83% of the 2007 and 2008 course freshman, respectively, completed a retrospective electronic survey in the final week of class in addition to standard MIT course evaluations.

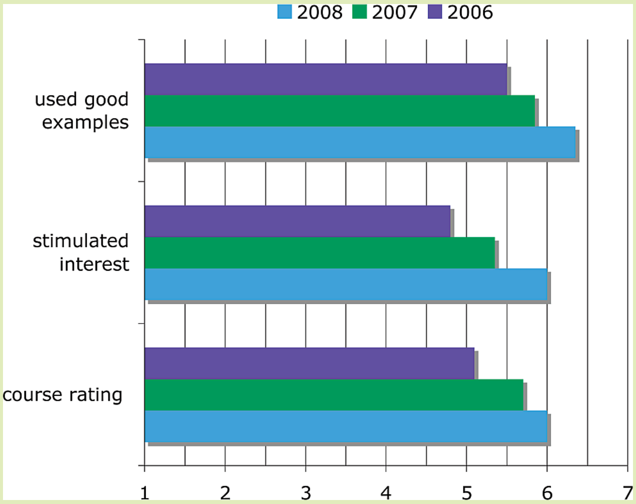
Assessment included student responses on current beliefs and attitudes about chemistry following the biologically enriched course and on the perceived impact of the course innovations in shaping these views. Following the course, students found chemistry interesting, expressed an interest in learning more chemistry, and strongly believed that in order to understand biology well, one must understand chemistry (see Supplementary Table 2, A−C). Students believed that chemistry is relevant to the field of biology and to medicine and other health care professions. They strongly disagreed with the statement that knowing chemistry is of minimal value unless a student intends to major in chemistry or a related discipline (see Supplementary Table 2, D−F).

Respondents credited the course for their positive views and attitudes. They reported that as a result of the course innovations their interest in chemistry and desire to learn more chemistry increased. Students also credited the course for their increased understanding of the role chemistry plays in other disciplines, everyday life, and health care (see Supplementary Table 3). Eighty-six percent of the students reported that the biology- and medicine-related examples helped them see the connection between biology and chemistry, mirroring the overwhelmingly positive course evaluation comments that the in-class examples "made me relate chemistry to other subjects", were "applicable to life", and "definitely increased my interest in the subject".

In addition to the TLL assessment, standard MIT course evaluations allowed for direct comparisons of student evaluations of the general chemistry course prior to implementation of the biology-related examples (2006), following implementation in only the second half of the course (2007), and after complete implementation (2008), with the caveat that while the curriculum remained constant, faculty changes occurred each year. There was a statistically significant increase between 2006 and 2008 in the overall course rating as well as in student assessment that the course instructors "inspired interest" in chemistry and "used good examples" (Table 2 and Supplementary Table 4). The quantitative assessment reflected the attitude of students' qualitative course assessment comments, with many conveying "I didn't like chem. when I started this class. I do now."

Dissemination. One priority in developing biology-related materials for our own general chemistry course was a low barrier for use of our material by other educators. While finding and creating examples can be prohibitively time-consuming for many professors and high school teachers, incorporating these examples into an existing course requires minimal instructor or class time, and the concise and modular format makes the examples amenable to use in even the most rigid chemistry curriculum. All of our in-class examples and biology-related homework problems are available through the MIT OpenCourseWare 5.111 Web site (*8*). The site has generated over 40,000 unique page views in the first full

TABLE 2. Mean student evaluations of general chemistry course 5.111 prior to implementation of biology-related examples (2006), with implementation in half of the lectures (2007), and with implementation throughout the course (2008)[a]



[a]All items are on a 7-point scale from 1 (poor or strongly disagree) to 7 (excellent or strongly agree). The rating differences between each consecutive year are statistically significant for all categories with the exception of "course rating", which is statistically significant between 2006 and 2007 but not between 2007 and 2008 (see Supplementary Table 4 for details). N = 135, 198, and 160 for the 2006, 2007, and 2008 data, respectively.

month online and also includes full video lectures and lecture notes.

Conclusion. We have developed and incorporated a set of biology-related examples and homework problems for general chemistry that encourage interdisciplinary thinking but have a minimal impact on class time and are easy and free to implement. With the recent budget and personnel cutbacks at colleges and universities nationwide, it is particularly important to consider teaching innovations that can strengthen undergraduate education without being costly in terms of faculty time, class time, or institute resources. Evaluation of our biologically enriched general chemistry course suggests that inclusion of biology-related examples can have a strong impact on undergraduate interest in chemistry, awareness of the role of chemistry in biological and biomedical research, and the realization that knowledge of chemistry is important for success in biology, medicine, and related fields. Incorporation of succinct biology and medicine-related examples in the general chemistry classroom is one strategy to adhere to the recommendations of the AAMC and HHMI to offer integrated courses and equip students with the skills to apply scientific principles (*3*). We anticipate that this and other forms of exposure to connections between chemistry and biology at an introductory college level can help foster more diversity in chemistry (*4*) and lead to a generation of scientists prepared to take on challenging and important interdisciplinary research (*1, 2*) and doctors able to integrate scientific advances into their medical practices (*3*).

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Supporting Information Available: This material is available free of charge *via* the Internet at http://pubs.acs.org.

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