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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 Association of American 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 pre-medical 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 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

Based on conversations with students and on course evaluation responses from past years, it was observed that MIT freshman enrolled in the non-advanced 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 two to five minutes 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 and atomic size, the selectivity of ion channels in neurons, able to distinguish between sodium and potassium ions, is used to illustrate the importance of a fraction of a nm 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). 86% 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 that, "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 website (*8*). The site has generated over 40,000 unique page views in the first full 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*).

References
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Table 1: General chemistry lecture topics and corresponding in-class biology and medicine-related examples. The examples and homework problems (not listed) are available online (*8*).

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 anti-cancer drug cisplatin
Crystal field theory, metals in biology	• Inspiration from metalloenzymes for the reduction of greenhouse gasses
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

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). 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 & 2007, but not between 2007 & 2008 (see Table S4 for details). N = 135, 198, and 160, for the 2006, 2007, and 2008 data respectively.
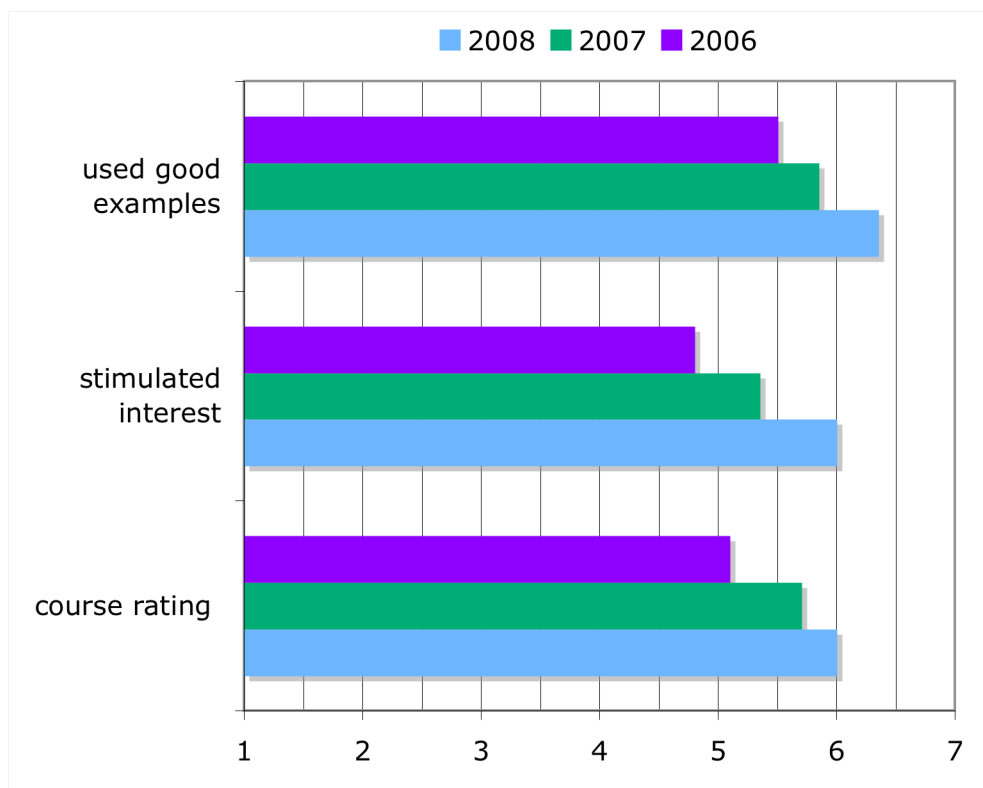
Supporting Information

Table S1: **Ethnicity data for 2008 freshmen participants**

	Frequency	Percent
1 African American	17	11
2 Asian	42	27.3
3 Caucasian	59	38.3
4 Hispanic/Latino	19	12.3
5 Native American	1	0.6
6 Pacific Islander	2	1.3
7 Other	14	9.1
Total	154	100

Table S2: Student beliefs and attitudes following course completion. All items are on a 7-point scale from 1 (strongly disagree) to 7 (strongly agree). Reported means and standard deviations (SD) are aggregated across student responses from 2007 and 2008.

	Mean (SD)	N
S2A. I find chemistry interesting.	5.75 (1.27)	343
S2B. I would like to learn more chemistry.	5.52 (1.54)	341
S2C. In order to understand biology well, one must know some chemistry.	6.13 (0.96)	343
S2D. Chemistry is relevant to the field of biology.	6.34 (0.74)	343
S2E. Chemistry is relevant to medicine and other health care professions.	6.59 (0.63)	342
S2F. Knowing chemistry is of minimal value unless a student intends to major in chemistry or a related discipline.	2.57 (1.36)	342

Table S3: Student reported impact of the biologically-enriched course (course 5.111) on student beliefs and attitudes. All items are on a 7-point scale from 1 (strongly disagree) to 7 (strongly agree). Reported means and standard deviations (SD) are aggregated across student responses from 2007 and 2008. For the 2007 students, for whom the biology-related examples were in only the second half of the course, the questions were instead prefaced with "As a result of **the second half** of 5.111".

	Mean (SD)	N
S3A. As a result of 5.111, my interest in chemistry increased.	5.31 (1.60)	343
S3B. As a result of 5.111, I am interested in learning more chemistry.	5.15 (1.68)	341
S3C. As a result of 5.111, I am more aware that chemistry plays a role in other disciplines.	5.42 (1.38)	343
S3D. As a result of 5.111, I am more aware that chemistry applies to everyday life.	5.29 (1.38)	342

S3E. As a result of 5.111, I see the relevance of chemical principles to biology, medicine, and health care.	5.72 (1.24)	343
S3F. As a result of 5.111, I have new insights into how chemistry might relate to my academic interests.	5.27 (1.50)	342

Tables S4A through S4E: MIT Course Evaluation Analysis

Table S4A: Descriptive statistics* of 2006, 2007, & 2008 course evaluations

Stimulated my interest in the subject											
		2006				2007				2008	
Instructor	M	SD	N	Instructor	M	SD	N	Instructor	M	SD	N
Dr. A	5.41	1.18	132	Dr. A	4.6	1.34	193	Dr. D	6.23	1.05	156
Dr. B	4.25	1.56	129	Dr. C	6.08	1.12	194	Dr. C	5.83	1.34	158
Provided good examples & illustrations											
		2006				2007				2008	
Instructor	M	SD	N	Instructor	M	SD	N	Instructor	M	SD	N
Dr. A	5.78	1.08	132	Dr. A	5.34	1.37	194	Dr. D	6.50	0.88	153
Dr. B	5.21	1.42	131	Dr. C	6.40	0.89	193	Dr. C	6.22	1.04	156
Overall Course Rating											
		2006				2007				2008	
Instructor	M	SD	N	Instructor	M	SD	N	Instructor	M	SD	N
Drs. A & B	5.15	1.29	134	Drs. A & C	5.72	1.04	193	Drs. C & D	5.99	1.22	155

*7-Point Rating Scale: 1=very poor, 7=excellent

For each semester, two professors each taught an half of the course. For the 2006 course, the two professors introduced no innovation. In 2007, Dr. C included biology examples in lecture and problem sets for the second half of the course. In 2008, Drs. C and D integrated biology examples into the entire course.

In Table A, the descriptive data represent the aggregate data of three survey questions included in the standard MIT end-of-semester course evaluation which relate to the biology example innovation. Because we wanted to run an ANOVA on each question and MIT provides only a condensed data set (mean, standard deviation and N) for students' anonymous responses, we proceeded as follows. In the case of the first two questions which relate to the teaching style of a specific lecturer and where data are provided in the aggregate by professor, we needed to compute a single mean $((n_1M_1+n_2M_2)/(n_1+n_2)$, standard deviation (pooled standard deviation), and N (n_1+n_2) for each year in order to perform an one-way analysis of variance (ANOVA). To compute the pooled standard deviation for each pair of instructors, we used the formula given below derived by Dr. Sanjoy Mahajan of the electrical engineering and computer science department. Table B provides the revised data for the two teaching style questions along with the overall course rating data. Tables C - E represent the ANOVA table for each item.

$$\sqrt{\left(\left(\left(\frac{n_1 n_2}{(n_1 + n_2 - 1)(n_1 + n_2)}\right)\left(\overline{X}_2 - \overline{X}_1\right)^2\right) + \left(\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{(n_1 + n_2 - 1)}\right)\right)}$$

The data reveal the following: For each item, the means increased from 2006 to 2008 as greater integration of biology examples into the course occurred. Post hoc comparisons indicate significant

differences between pairs of years for each item except for the smallest difference, the 2007-2008 comparison of the overall rating,

Although the students rated both professors in the same survey, the Mahajan formula for the pooled standard deviation treats the two sets of responses as if they came from two separate groups of respondents. As a result, the assumption of independence may have been violated leading to an inflated alpha for the ANOVA. However, the ANOVA data for the overall course rating are based on a single set of mean, standard deviation, and N for each year; and, this data produce findings consistent with the other two questions. Moreover, the probability of all three items is < .000 which suggests that even if an inflation of alpha occurred for the first two items, the inflated alphas for those ANOVAs would not be of order of an magnitude that would refute the claim of significant differences.

Table S4B: Comparison of Student Course Evaluations for 2006, 2007, & 2008

	2006			2007			2008			One-Way ANOVA[1] p	Post Hoc Comparisons Tukey's HSD[2] $p \leq .05*$ $p \leq .01**$
Question	Mean	SD	N	Mean	SD	N	Mean	SD	N		
Stimulated My Interest in the Subject[3]	4.84	1.50	261	5.34	1.44	387	6.03	1.22	314	0.000	2006 & 2007** 2007 & 2008** 2006 & 2008**
Used Good Examples and Illustrations[3]	5.50	1.29	263	5.87	1.27	387	6.36	0.97	309	0.000	2006-2007** 2007-2008** 2006-2008**
Overall Rating of the Subject[3]	5.15	1.29	134	5.72	1.04	193	5.99	1.22	155	0.000	2006-2007** 2006-2008**

[1]A one-way ANOVA is a technique used to compare means of two or more samples using the F distribution.
[2]Tukey's HSD (Honestly Significant Difference) test is a single-step multiple comparison procedure and statistical test generally used in conjunction with an ANOVA to find which means are significantly different from one another.
[3]7-Point Rating Scale: 1=very poor, 7=excellent

Table S4C: ANOVA table showing calculations involved in computing the F[1] statistic for the MIT course evaluation survey item - *stimulated my interest in the subject.*

Source of Variation	Sum of Squares	d.f.	Mean Square	F	p
Between Groups	207.0286	2	103.5143	53.6225	0.000
Within Groups	1851.2788	959	1.9304		
Total	2058.3074	961			

[1]F-statistic is a value used to determine if the variances among means of different populations are significantly different. Between groups refers to differences **between** individual means and the grand mean and within groups refers to differences between individual data and the group mean **within** each group.

Table S4D: ANOVA table showing calculations involved in computing the F statistic[1] for MIT course evaluation survey item - *used good examples & illustrations.*

Source of Variation	Sum of Squares	d.f.	Mean Square	F	p
Between Groups	107.1437	2	53.5718	37.9826	0.000
Within Groups	1348.3708	956	1.4104		
Total	1455.5145	958			

[1]F-statistic is a value used to determine if the variances among means of different populations are significantly different. Between groups refers to differences **between** individual means and the grand mean and within groups refers to differences between individual data and the group mean **within** each group.

Table S4E: ANOVA table showing calculations involved in computing the F Statistic[1] for MIT course evaluation survey item - *overall rating of the course*,

Source of Variation	Sum of Squares	d.f.	Mean Square	F	p
Between Groups	52.3624	2	26.1812	19.053	0.000
Within Groups	658.2061	479	1.3741		
Total	710.5685	481			

[1]F-statistic is a value used to determine if the variances among means of different populations are significantly different. Between groups refers to differences **between** individual means and the grand mean and within groups refers to differences between individual data and the group mean **within** each group.