“The Chemistry of Poisons”: An Interdisciplinary Approach to Integrating Chemical, Toxicological, and Medicinal Principles

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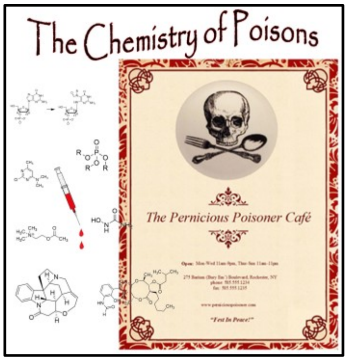
ABSTRACT

An interdisciplinary course called “The Chemistry of Poisons” was created, featuring organic chemistry, biology, pharmacology, and toxicology content. This exploratory chemistry elective course was created by an instructor with a background in synthetic organic chemistry and a teaching assistant with a background in pharmacy practice. The Chemistry of Poisons features an interdisciplinary, student-centered approach to learning that provides a foundation for future academic initiatives to deliver chemical, pharmacological, and humanistic content in a manner that is both enjoyable for students and demonstrably facilitates knowledge and application level learning. Student course feedback and a retrospective survey were used to gauge student-perceived learning achievement. Survey results and feedback were consistent with knowledge and application level learning of course content and preference for interdisciplinary course design. These results warrant further development and study of interdisciplinary strategies for chemical education.

TABLE OF CONTENTS GRAPHIC



KEYWORDS

Upper-Division Undergraduate, Graduate Education / Research, Curriculum, Interdisciplinary / Multidisciplinary, Organic Chemistry, Problem Solving / Decision Making, Applications of Chemistry, Learning Theories, Toxicology

INTRODUCTION

Traditional scientific taxonomies differentiate disciplines by content domain, and the specific research practices and methods used are not often shared across disciplines. Thus, studies in individual disciplines are circumscribed by specialized topics and specific modes of inquiry and analysis. When content or methodology from two or more traditional disciplines are studied concurrently, the work is termed multidisciplinary, interdisciplinary, or transdisciplinary depending upon the degree of content integration. Exactly how these three terms should be applied to specific courses and activities is ambiguous due to the nuances involved when presenting integrated information. In theory, the term interdisciplinarity refers to a continuum of progressive content integration and interactivity; from integrated (multidisciplinary), to hybridized (interdisciplinary), to transformed (transdisciplinary).[1] Despite potential direct and indirect benefits of collaboration, interdisciplinarity has a number of challenges and limitations. Educators, researchers and administrators must define the integrated scope and maintain and evaluate working relationships throughout the interdisciplinary undertaking, while maintaining awareness of predisposition to work within the familiar confines of their respective disciplines.[2] Furthermore, the probability of success decreases as the disciplinary content areas become more distal.[3] Therefore, despite its potential promise as an educational strategy, the "activation energy" barriers to interdisciplinarity and the exploratory nature of novel collaborations necessitate further investigation of interdisciplinary learning.

The rate of publications involving interdisciplinarity has increased since 1990, particularly in the context of education research.[4] Examples of interdisciplinarity in science education are plentiful and varied in scope, setting, content, and design. For example, the use of technology and media in secondary science education, by way of concept mapping, demonstrated benefit for conceptual learning of biological and physical principles of hibernation and thermodynamics.[5] A similar undergraduate-level activity incorporating perspectives of multiple physical sciences analyzed the thermodynamic considerations of biologically relevant high energy bonds.[6] In addition to curricular components such as science coursework and experiential education; teamwork, affiliation, and human interaction are prescribed outcomes for the education of healthcare professionals, with examples of interdisciplinary exercises typically taking place in clinical rather than classroom settings.[7-9] The inception and continued development of interdisciplinary chemistry courses, which feature learning of chemical principles by way of non-chemistry topics, affords instructors new and interesting opportunities to conduct chemical education. Analysis of publications in science and chemistry education research from 2004-2013 demonstrates plentiful examples of interdisciplinarity including:

- an interdisciplinary course addressing the biology and chemistry of brewing[10]
- chemical software development[11]
- analysis of the art and science of light[12]
- environmental science[13]
- toxicity of nanoparticles[14]
- problem-based learning in biochemistry[15]
- strategies to address chemical misconceptions[16]

To be successful, such interdisciplinary undertakings each reported careful attention to course or activity design, clear learning goals, efficient collaboration, and optimal content integration.

Topics involving toxicology are inherently well suited for interdisciplinarity. The biological activity of toxic molecules, and their impact on the human experience, is of professional interest to scientists and health care professionals, and of general interest to undergraduate students studying everything from sciences to humanities. Examples of successful interdisciplinary activities centered on chemistry and poisons include the integration of *The Poisoner's Handbook* into undergraduate chemistry courses,[17] the application of forensic science to analysis of literary classics and fictional crime scenes,[18,19] and the discussion of chemical phenomena that may have inspired operatic plots.[20] To add to and build upon these examples, we describe the development, goals, activities, and outcomes of an interdisciplinary course entitled "The Chemistry of Poisons."

METHODS

Course Design

The course was conducted for the first time in spring 2015, as a pilot course in the Department of Chemistry intended to explore analysis and discussion of poisons from multiple perspectives. It was an unusual offering, in that it was neither a service course for science majors nor an upper level course for primarily chemistry majors. The initial design and implementation was carried out by the authors; an instructor with a background in synthetic organic chemistry and a teaching assistant (TA) with a background in pharmacy practice, as a 4.0 credit hour, lecture-based course with weekly workshops. In the absence of established precedent for the course, the instructors were unsure how it would be received by students, and anticipated changes and the need for flexibility in its design based upon student feedback and performance. Therefore, course development continued during these first three years (2015-2017), with interdisciplinary study a consistent priority. In its first two years, 2015 and 2016, course content drew from three different disciplines: organic chemistry/ biochemistry (lecture and workshop), pharmacology (workshop), and the humanities (literature, history, and anthropology through assigned readings and written assignments, and occasionally, discussion in lecture). In 2017 the content of the workshops shifted from pharmacology to organic chemistry due to changes in teaching assistant personnel. Although this departure diminished the interdisciplinary nature of the course, the residual impact is maintained in its design. Additionally, pharmacology content was compiled, summarized, and delivered by the former TA for subsequent iterations of the course. The course timeline is provided in Table 1.

Table 1: Years one through three of a new course: "The Chemistry of Poisons"

Course Year	*Enrollment [a] /Cap [b]*	*Instructor Background*	*TA Background [c]*	*Workshop Focus*	*Final Project*	*Souvenir*	*Post-course Survey*
2015 (Year 1)	32/35	A. Frontier, PhD, Synthetic organic chemistry	D. Austin, PharmD, first year PhD Student	Pharmacology & organic chemistry	Wikipedia article	Poisonopoly	2017
2016 (Year 2)	27/30	A. Frontier, PhD	D. Austin, PharmD, second year PhD Student	Pharmacology & organic chemistry	Poster presentation	Poisoner's Handbook	2017
2017 (Year 3)	45/45	A. Frontier, PhD	S. Abdul-Rashed, first year PhD Student	Organic chemistry	Wikipedia article	Poisonous Menu	2017

[a]Number reflects enrollment at conclusion of course
[b]Maximum enrollment determined by instructor
[c]University of Rochester Department of Chemistry

The course explores the science of poisons on the molecular level, their impact on humanity, and it examines the relationship between poisonous molecules and medically important ones. The topics of the curriculum are focused on naturally occurring, non-peptide organic poisons. The molecules discussed are primarily isolated from biological sources, including plants, fungi, animals, and microorganisms. The large peptidic poisons of venoms were excluded in order to maximize the emphasis on chemical concepts associated with small molecule poisons.[21] Chemistry topics include chemical and biochemical mechanisms of toxicity (at the molecular level), as well as biosynthesis and chemical synthesis of the small molecules. The course also explores the historical and cultural influence of poisons through popular science texts, historical texts, literature, essays, and popular culture; including television, music, and film.

Regarding course objectives, by the end of the semester students are expected to be able to:

1. Articulate what makes a poison a poison, and describe factors that determine how dangerous a molecule is
2. Appreciate and explain how poisons impact our lives in both positive and negative ways in the context of human and animal health, the environment, as well as their impact on mythology and storytelling
3. Understand how scientists study these molecules: the design of experiments, analysis of data, and isolation or synthesis of these molecules in the lab

Furthermore, when graduates of this course encounter a new example of a poison in the news or in popular culture, they are expected to be able to put the new poison into context through analogy to poisons studied in class, and explain its significance in a general way to both their peers and those without a background in science or healthcare. Thus, students learn to appreciate the diversity and ubiquity of biologically active small molecules through the lenses of: chemistry, pharmacology and humanistic studies; and to ultimately appreciate that poisons and medicines are “two sides of the same coin.” The Chemistry of Poisons not only provides a window into the captivating science and history of poisons, it also provides non-traditional, supplementary preparation for careers in science, industry, and health professions.

During the scientific components of the lectures, the simplest substances (e.g. cyanide, ethanol) are introduced first, along with their biological targets and mechanisms of action. Students are introduced to new terminology and concepts relevant to organic chemistry, biochemistry, medicinal chemistry, and toxicology; ideas and vocabulary that are solidified and built upon in subsequent lectures. As the course progresses, so does the complexity of the chemical structures, and more comparisons are drawn between mechanisms of action of different poisons and their targets. By the end of the course, students have gained familiarity with multiple small molecule-target interactions, and they understand the similarities and differences between how these systems function. Students are introduced to concepts in anatomy & physiology and pharmacology, and to the use of biological systems to analyze the chemical effects of small molecules. In examining small molecules considered “poisons,” students are able to build upon and deepen their understanding of the advanced organic chemistry principles discussed in the course. The culmination of content delivery features the opportunity for students to apply knowledge gained from the course in order to complete a final project.

Lectures are supplemented by workshops that provide students the opportunity to problem-solve using concepts from lecture material, with the guidance of a graduate student TA. When the course is staffed with a TA who has expertise complementary to the instructor’s, there is opportunity to introduce concepts and terminology of pharmacology, toxicology, and professional practice in health care during workshop time. The resulting interdisciplinary workshops contained a mix of exercises that required application of chemical knowledge and introduced principles of pharmacology, toxicology, and molecular biology in a problem-based learning format. For example, during the first iteration of the course, a workshop was devised to complement lecture content focused on acetylcholinesterase inhibitors as poisons. Concepts and mechanisms of poison-receptor binding, aging, and reactivity were discussed in lecture, along with the effects of poisoning. The corresponding workshop introduced students to anatomy and physiology of the autonomic nervous system, and featured practice problems and cases that reinforced lecture content.

Formal assessment is conducted by a mixture of summative examinations, weekly written homework assignments, and a final project. The final project in the course requires both scholarly research and the creative application of the formal course content. Examples of assignments that have served as the final project include contributing to or creating a Wikipedia page (solo), revising and creating connections within a set of pages (as a member of a team), or assembling and presenting a scientific poster. Homework assignments each week constitute the humanistic component of the course. Students are assigned fiction or nonfiction readings, or sections of a television show or film, and they are asked to write a brief response to a specific prompt. Informal assessment occurs throughout the course by way of in-class discussion, and student-led completion of workshop activities. The diverse modes of instruction and assessment, along with the feedback mechanisms built into The Chemistry of Poisons, encourage creative analysis of media, active learning, and development of critical thinking and problem solving skills. The 2016 course syllabus, homework assignment examples, an exam, and the rubric for the final project (Wikipedia article) are contained in Appendix A.

Student Background & Preparation

Organic Chemistry I and II are pre-requisites for enrollment in The Chemistry of Poisons. As a consequence of this requirement, the students are typically juniors and seniors. They are nearly all science or engineering majors, or pre-medical students, or both. Despite this prerequisite, students enter the class with different comfort levels, confidence, and training in organic chemistry, depending on whether they performed well in the introductory courses, how many years have elapsed since they completed them, and whether they had additional exposure to organic chemistry topics through additional coursework or by serving as a TA. It is possible to take the course for 400-level (graduate) credit, an option that was instituted to allow chemistry students pursuing a BS to satisfy a major requirement.

These students completed additional research requirements associated with the final projects. All of the students in the course were undergraduates, with only one exception for a first year graduate student. Academic majors for students enrolled over the period 2015-2017 can be broken down into four general categories: biology (52%), chemistry (22%), engineering (19%) and other (7%). Specific majors included:

- molecular genetics
- cell and developmental biology
- neuroscience and psychology
- biochemistry
- chemistry
- British and American literature
- chemical engineering
- epidemiology
- biomedical engineering
- public health

For students majoring in the sciences, the course counted as an upper level chemistry class (a 4-credit "technical elective.") The course enabled many students to earn a minor in chemistry, as one of the six 4-credit chemistry courses available. Students who completed the course have moved on to education programs or employment including:

- graduate school for various scientific disciplines
- medical school
- dental school
- chemical engineering
- education
- research scientists
- information technology specialists
- software engineers
- lab technicians

In-class Activities

Traditional lecture is supplemented with in-class activities as determined by the nature of the content being covered. For example, mechanisms of pertinent organic syntheses and reactions are demonstrated and explained by traditional "chalk talks." Overviews, historical topics, and background biochemistry are typically presented as slide show presentations. Additional situation-specific activities are also conducted during class time. Examples include a simulation of poison-receptor binding and binding effects, watching and analyzing an episode of the medical drama *House, MD* that features poisoning, hosting guest lecturers, and soliciting student volunteers to read scenes from Shakespeare's *Romeo and Juliet*.

Workshops

For workshops the class is divided into groups of eight to ten students, with each group attending a scheduled one hour meeting outside of class. Workshop problems were prepared collaboratively by the course instructor and teaching assistant to merge chemical, pharmacological, and toxicological perspectives into interdisciplinary content. Content covered in workshops includes topics involving chemistry, pharmacology, and healthcare delivery. Students work individually or in pairs to address the problems, and then take turns leading the discussion, which is facilitated and moderated by the teaching assistant. These sessions provide ample opportunity for application of topics introduced during lecture, as well as a different instructor's point of view on the course material.

Reading & Response Assignments

The weekly assigned readings and responses (~25% of grade) are not scientific in nature; rather they represent a literary or historical counterpart of the chemical course content that week. The assignments range from historical accounts and descriptions of poisonings, to selections from literature, excerpts from TV, film, or mythology associated with poisons, to modern opinion pieces and essays. Examples of readings include fiction such as: *The Mysterious Affair at Styles* (Agatha Christie), *The Count of Monte Cristo* (Alexander Dumas); and non-fiction such as *LSD My Problem Child: Reflections on Sacred Drugs, Mysticism, and Science* (Albert Hofmann), *The Serpent and the Rainbow* (Wade Davis), *The Island of the Colorblind* (Oliver Sacks), and television episodes from *House, MD* and *Bones*. After reading or viewing, students are asked to write a 450 word (max) response to the week's prompt, which often does not have a specific "right" or "wrong" answer; student performance is instead assessed based on demonstrating understanding of concepts, constructing a sound argument based on conceptual understanding, and overall rhetorical quality. The students are asked to make an argument based upon their personal opinions, as influenced by their interpretation of the media, along with any other sources they choose to consult on the topic. These exercises also provided the basis for thought-provoking in-class conversation and debate, engaging students and leading to wide-spread participation in class discussion. Unit-based summative assessments are implemented as written exams (two exams worth a total of ~40-45% of grade), which are comprehensive and include information and concepts from readings, lecture, and workshops.

Final Project (individual) and Souvenir (collaborative; derived from individual final projects)

The final project is the capstone experience of the course. Each assignment is unique, in that students are given a different small molecule to research and present. Two different outlets have been used to present the findings of the independent project: one is the writing or extensive editing of a Wikipedia page or pages on the topic, and the other is the preparation of a scientific poster that is presented during a poster session offered to the public at the end of the semester. The instructor selected the format of the final project at the beginning of the term. For both project formats, one class period was spent discussing the format and strategies for communicating successfully within that format. Following this lecture discussion, two to three in-class or homework assignments were devoted to:

a. Consideration of audience (who will read what you write, who will discuss your poster with you?)
b. Criticism (what organization/ content works and doesn't work in a Wikipedia articles, or a poster?)
c. Outlining (a graded assignment, passing grade required to move onto the draft. Feedback provided by the instructor, and revisions may be requested)
d. Peer feedback exercises

The project, in either form, offers opportunities for creativity and metacognition, as it is necessary to identify and address the intended audience for the subject matter in order to choose appropriate scope and depth of scientific content. Since images and other visuals are critical to communicate the history, chemistry and medical implications to the audience; students must also prepare content that is aesthetically appealing, effective for their topic, and accessible to their audience. An unexpected feature of the projects has been the importance of curation: what should be included, what should be left out, and how much detail is ideal? All things considered, the project requires independent scholarship, demands creativity and an interdisciplinary approach, and is a rewarding experience for students. The final project serves as a final exam in the course, and is assessed according to a rubric.

As a class, students are also asked to propose a creative format to collect, integrate, and highlight exciting information from all of the final projects. This "souvenir" is intended to be a physical item to take home with them that contains a contribution from each student's scholarly final project. Ideas for this collaborative effort are solicited from students early in the semester; students are given the opportunity to advocate for different ideas, and finally after discussion, a vote is taken to select the final format. During the execution of the scholarly project, students are asked to extract a suitable general synopsis, including appropriate images that can be incorporated into this course-wide collaboration.

In order to assess and present the course, specific examples of the elements listed above are contained in the following section. Additionally, students who took the course 2015, 2016, or 2017 were requested to take a retrospective survey (all students took the survey at conclusion of spring 2017 term) to gauge student-perceived course design, learning achievement, and for general feedback about the course. This study was reviewed by the University of Rochester Institutional Review Board and met criteria for exemption.

RESULTS

Examples of Souvenirs

Examples of souvenirs include a poisons-based board game, compiling entries for a "Poisoner's Handbook," and a "Poisonous Menu". The cover of a final project, "The Pernicious Poisoner Café," along with two "poisoned" beverages are shown in Figure 1. In all of its incarnations, the souvenir has effectively presented the scientific topics in a format accessible to the general public, and allowed students to learn from each other by sharing the highlights of their research topics with their classmates.

Pennyroyal[1] Mojito - $10

Tired of not going out due to stomach pain? Going to let the flu, a cold, or *fleas* keep you home? Well jump of bed and come fetch this all in one magical, medical, fun-inducing cure! Our Pennyroyal Mojito is made with lime juice, sugar, white rum, club soda, 7 fresh mint leaves and 7 sprigs of our freshest European pennyroyal. Or...if you're feeling a bit on the deviant side...you can also request a substitute for pennyroyal oil, if you wish to make its consumer go unconscious, go into shock, experience seizures and hallucinations, and more! Pennyroyal oil is highly concentrated and tastes like spearmint, which intensifies the mint flavor of our mojito. Careful though, ladies--pennyroyal is best known for its ability to induce menstruation, and abortions. Best to know what you're getting into. The classic mint drink is an excellent pairing with our N-Nitrosonornicotine Nachos.

The Strangler - $10.99

"Fast. Effective. Perfect for a shocking moment at any occasion."
~ Lord Petyr "Littlefinger" Baelish, Master of Coin

"Helps me avoid pesky soon-to-be in-laws."
~ Lady Olenna Redwyne, "The Queen of Thornes"

Figure 1. Examples of Fictional Poisoned Beverage from "The Pernicious Poisoner Café"

Example of Lecture Content: Advanced Mechanisms in Organic Chemistry and Biochemistry

Since the course is taught by an organic chemist, it focuses on molecules that act through covalent or radical mechanisms over molecules that act through simple intermolecular binding interactions. One example is the activity of calicheamicin, an antineoplastic agent. Students learned how this molecule (and other ene-diyne antibiotics) is activated to generate high-energy, radical intermediates, which can then react with the carbohydrate backbone of DNA, ultimately achieving cleavage of double-stranded DNA.[22] The initial chemical reactions that comprise the mechanism of action of calicheamicin are shown in Figure 2.

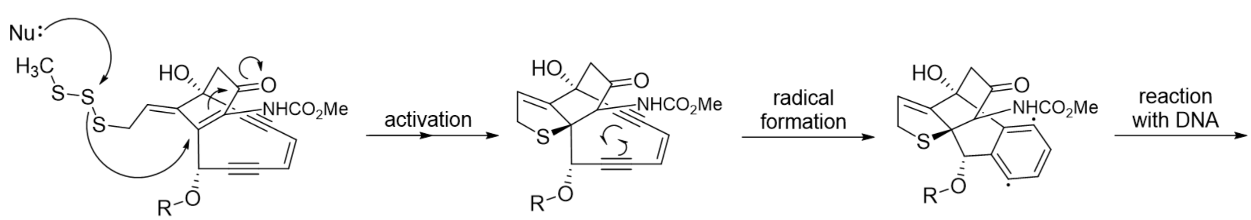


Figure 2. Mechanism of Reaction of Calicheamicin with DNA

Example of Workshop Activity

Workshops activities introduced pharmacology and toxicology definitions and topics. These topics were then used, along with knowledge of chemical principles discussed in class, to address complex, integrated problems. A problem from the workshop entitled "Introduction to Concepts in Pharmacology" (2015) is shown in Figure 3:

> Strychnine is a potent alkaloid rodenticide. Its pharmacodynamics involve antagonism of the neurotransmitter glycine. Glycine has a postsynaptic inhibitory effect. The LD_{50} when ingested orally is about 1.5 mg/kg. It has an average apparent volume of distribution (V_D) of 13 L/kg. Strychnine sulfate is soluble, while strychnine bromide is not. Use this information for the following poisoning case question:
>
> El, a 50 kg female, had been taking strychnine SO_4 solution as a stimulant for the past two years in addition to other medications. Her usual dose was one teaspoonful (5 mL) of 2 mg/mL solution once daily in the afternoon as needed. She reportedly used it on a daily basis, and stored it after opening it in her private room. She obtained refills of her 150 mL bottle regularly, and she consumed the final dose of the bottle earlier today (1/20). Later she was found dead in her room, presumably due to strychnine poisoning (strychnine, sulfate, bromide, phenobarbital, and aspirin were detected in her blood). After speaking to her house staff, authorities determined that her private room was accessed in the evening two days ago (1/18), and in the morning eight days ago (1/12).
>
> A. How was El poisoned, and what dose of strychnine did she consume; is this surprising based on the LD_{50}?
>
> B. Using the formula: $C_p = \text{Dose} / V_D$ (C_p = plasma concentration)
> What is El's expected plasma levels after consumption of the fatal dose?
>
> C. After a thorough investigation, authorities determined that El died approximately 3 hours after consumption of the strychnine. This was surprising as death usually occurs within an hour. Provide a plausible explanation for this observation.

Figure 3. Example of a Workshop Problem

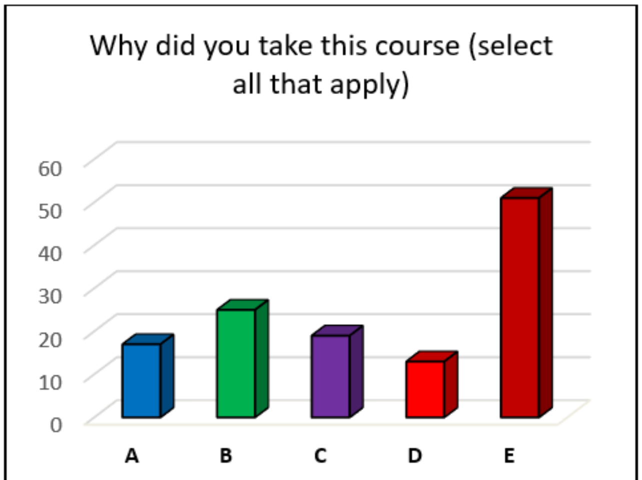
Example of Reading/Response Activity

Students are asked to read a chapter entitled "Toxicology" in the novel *The Count of Monte Cristo* (Alexander Dumas, 1844). In this chapter, the protagonist Edmond Dantès (a self-proclaimed expert in the field of toxicology), walks his interlocutor through several examples of accidental and deliberate poisonings as a means of explaining the scientific phenomena underlying the cases. The prompt for the 450 word response that week is "How accurate is Mr. Dantè's analysis, given what you (a 21st century scientist) know about the subject? Choose three of the cases he discusses and point out the true and the false in his explanation."

This assignment is given relatively early in the semester. Students find that as they build upon their knowledge of toxicology, they revise their opinions of Dantè's analyses. In many cases, students discover that his thinking was more accurate they originally thought, and realize that the nuances of each case make it difficult to draw conclusions without collecting more data.

Student Feedback

The most common reason for taking the course was intellectual curiosity, while the least common reason was relevance to career goals. Student responses to the question “why did you take this course?” are displayed in Figure 4. These responses were obtained from students who took the course in 2015, 2016, or 2017. Over its first three years, the course was popular with students, as demonstrated by an increasing selection of the response “It was recommended by other students.” Five students from the 2016 cohort and 14 students from the 2017 cohort selected this response, which indicates that the emerging population of students who had taken and completed the course was recommending it to peers.



Answer Choice	Answer Text
A	To earn credit for my major (chemistry)
B	To earn credit for my minor (chemistry)
C	It was recommended by other students
D	It was relevant to my career goals
E	Intellectual curiosity

Figure 4. Survey Responses

Students of the course have offered useful feedback, which has contributed to the ongoing development and evolution of the course. In addition to standard course evaluations, beginning in 2017 students provided information to the following questions:

1. What did you find unexpected about the course?

2. What was surprising about the course?
3. What was memorable about the course?

Student answers to these questions demonstrated the breadth and integration of content covered, as well as capacity for heterogeneous experience of the course. Selected responses of the students of the spring 2017 course are listed in Table 2:

Table 2: Student Feedback at Conclusion of the Course (2017)

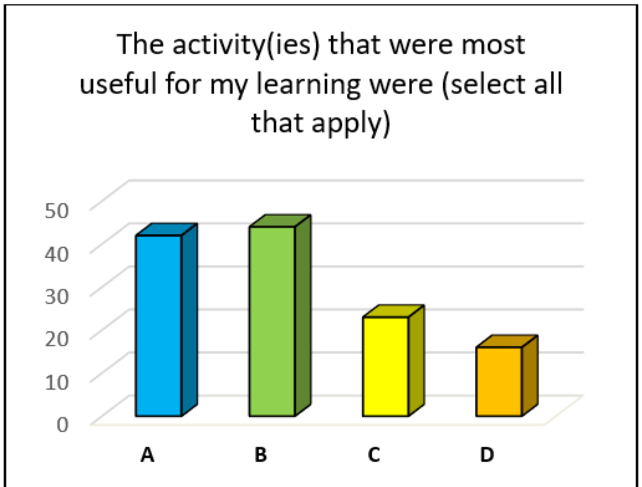
Unexpected	***Surprising***	***Memorable***
How simple some poison's structures are	To learn that so many different mechanisms of actions of poisons are possible	Potatoes and tomatoes are members of the nightshade family
That there are so many different poisons that act in so many different ways	Many poisons were once thought to have legitimate medical applications	The stories I read
The historical impact of poisons	The ocean is full of "chemical weapons"	Optimization of biological activity of drugs and poisons
The chemical pathways associated with synthesis or activity of poisons	Importance of dose in determining poisonous activity	Links poisons to real-life cases
Cultural influence of poisons; how almost normal it was in everyday life	Need to understand a lot more biology than I expected	The book "Serpent and the Rainbow"
Amount of chemistry involved with historic events	That there may be historical basis for "zombies"	Learning about drug addiction and drug interactions
I'm better at chemistry than I thought	The readings were engaging and interesting	A lot of opportunity for clinical application of this knowledge

Students were additionally requested to provide feedback pertaining to what they enjoyed in the course, which activities they found to be most useful for their learning, and how the course could be improved. Selected responses from students from the 2015, 2016, and 2017 classes are shown in Table 3 and Figure 5.

Table 3: Additional Student Feedback at Conclusions of the Course (2015-2017)

What did you enjoy most about the course?	***How could this course be improved?***
The final project was easily my favorite part of the course. I loved making a new Wikipedia page!	It felt like it jumped around a bit so maybe just a little more structure
The interesting stories and historical context being integrated	More time spent on the chemistry--it was hard for me to understand mechanisms sometimes
The interdisciplinary things for one. I always liked moving between the bio, chem, history, and lit parts of	As someone who's very interested in bio, I'm obligated to say bring a bit more of the biological systems into the

the course, it's part of the reason I'm an english major and chem and bio minor. I also really enjoyed just learning about the poisons in the world because it's just... INTERESTING! I wanted to learn about poisons to apply them to my own writing and cause it's cool, and guess what, that happened and it was awesome!	course. I was always interested in some of the more specific effects/symptoms were for the poisons we talked about, and while it was relatively easy for me to look up (barring the fact that I'm certainly on a homeland security watch list b/c of it) it still would have been nice to hear from the prof.
I greatly enjoyed he intersection of anthropological/critical thought via the B.B. writing homework's and the application of chemistry. I also liked how intricate the mechanisms of the poisons were and that the chemistry was applicable.	More integration of some biological or physiological principles could help put the biological effects of some of the poisons discussed into context.
It was intertwined with literature and history. It was fun to learn about chemistry from this different perspective.	Shorter more modern readings would help to make the course even more relevant and support the lecture material.
The interactive workshops and novel lecture style	More continuity between each lecture/workshop.
I liked how we covered the chemical, biological, and cultural aspects of poisons.	Spend more time on the final Wikipedia project
That said, I THOROUGHLY appreciated this course as one of the only (if not THE only) course in my major that explored the history of poisons and chemistry beyond an understanding of the biological and chemical mechanisms. This was my favorite course within the major because it explored the wealth of connections between chemistry and interdisciplinary fields of knowledge. Bridging chemistry into other fields such as history, fiction, and our social conceptions of its knowledge helped shape my understanding of chemistry as more than matter and its interactions. This course was a driving force in my consideration of chemistry beyond its natural science component - it helped me to bring my learning into social and cultural understandings of the field of chemistry.	There was not much I would improve upon this course. The only thing I can think of that could potentially be an interesting assignment within the course is having students not only find a fictional poison, but have them attempt to propose a mechanism of action for this fictional poison based on its properties. We may have done this together in class at some point, but I think it would be beneficial for students to try to do this individually or in small groups.
It's hard to choose! I loved the combination of biology and chemistry - this helped me to understand the mechanisms of poison on so many different conceptual levels. I don't know that I could have gotten a better understanding if I had learned from just a biological or just a chemical perspective. Additionally, this was the first time I took a science course that related to history/media/novels. I think understanding the context of the world when these events took place is very insightful, especially as we move into the "real-world" and try to explain our scientific research to the general public.	Perhaps if an assignment would be "What did Oliver Sacks think about X?" then immediately having another question like "Propose an arrow pushing mechanism of X with Y"



Answer Choice	Answer Text
A	Lectures
B	Workshops
C	Assignments (Homework & Readings)
D	Final Project

Figure 5. Survey Responses

Students were surveyed to assess learning outcomes associated with The Chemistry of Poisons on the basis of discipline, taxonomy, feedback, and overall experience. Questions asked using a five-point Likert scale are shown with results in Table 4 (0 = strongly disagree; 5 = strongly agree).

Table 4: Student Survey Results

Question Number	***Survey Question***	***N***	***Average***	***Standard Deviation***
1	After taking this class, I would say I have an excellent appreciation of how poisonous substances have shaped human history	55	4.36	0.589
2	After taking this class, my understanding of the mechanisms of actions of poisons improved significantly	55	4.64	0.589
3	Having taken this course, I can evaluate the accuracy of fictional media involving poisons	55	4.13	0.721
4	I could explain real-life situations involving poisons to people who have little or no scientific training	55	4.33	0.721
5	This class contributed to significant improvement of my general problem solving skills	54	3.54	0.770
6	Simultaneous study of both chemical and biological principles of poisons improved my understanding of chemical behavior of poisons	54	4.52	0.574
7	Simultaneous study of both chemical and biological principles of poisons improved my understanding of biological activity of poisons	53	4.45	0.574

8	Studying the chemistry and biological activity of poisons separately (e.g. in different courses) would have made learning more efficient	54	2.24	1.01
9	Studying both science and non-science content at the same time was useful for my learning	54	4.24	0.799

Students elected to take The Chemistry of Poisons for multiple reasons, most notably for "intellectual curiosity," and reported breadth of variety in what they took away from the course. In order to investigate potential year-to-year variability to assess the longitudinal nature of these results, statistical analysis was conducted to compare response means across the three course years of student respondents. Significant interclass variability was determined by ANOVA (significance = $P < 0.05$) for only question two: "After taking this class, my understanding of the mechanisms of actions of poisons improved significantly" (2015 class: 4.76, 2016 class: 4.29, 2017 class: 4.75; $P = 0.033$).

DISCUSSION

Students reported lecture and workshops as being the most useful course elements for their learning (Figure 4), which is consistent with the notion that strategic design of interdisciplinary learning activities implemented through traditional teaching techniques is a useful strategy to promote student engagement, enjoyment, and critical thinking. The Likert survey questions were designed to provide a measurable medium through which students could analyze retrospective, self-assessed achievement of learning in the class. The first three questions of Table 3 directly assessed course-specific, knowledge-level learning of course outcomes, and averages above 4.00 for each question ("agree") are consistent with achievement of these outcomes. Analysis of survey results suggests that the favorable, self-assessed learning responses and reception to The Chemistry of Poisons are primarily associated with the core construct of the course as delivered by the primary instructor, given robust results despite modification of specific content, variability in projects and assignments, and variability in workshop instruction conducted by multiple teaching assistants throughout the evolution of the course. Furthermore, only question two, "After taking this class, my understanding of the mechanisms of actions of poisons improved significantly" demonstrated variability based on which year the course was taken, as indicated by a drop in score from 2015 to 2016 (4.76 to 4.29). No other responses were significantly different for that year, which demonstrates the robustness of the core construct and the latency of its interdisciplinary design despite

TA personnel changes. It also underlines the value of assembling a team with complementary areas of expertise. Results shown in Tables 2 and 3 demonstrate evidence of the thought provoking nature of this design. Students explicitly mentioned positive affective and cognitive response to “learning about chemistry from a different perspective,” content integration, discussion of historical and fictional content, and interactive workshops. The subsequent questions required metacognition, and were designed to assess response to interdisciplinary course design in regards to response to content integration and comprehension and application level learning objectives. Reponses to question four are consistent with learning on par with the first three questions, and question five results were above 3.00 (“neutral”) that the course directly contributed to significant improvement of problem solving skills in general. Questions six through nine explicitly addressed interdisciplinary course content, and all results were consistent with benefit derived through the interdisciplinary course design.

Potential limitations of this analysis include attrition, recall, and selection bias: the voluntary, anonymous survey was administered up to two years following completion of the course, and student perception and recall may be influenced by this lag. Additionally, students who enjoyed and/or were successful in the course may have been inherently more likely to complete the survey than their counterparts who did not enjoy and/or did not achieve a desired grade in the course; a total of 55 students participated in the survey, which constitutes just over 50% of the students who took the course between 2015 and 2017. In the absence of an established valid and reliable survey instrument for assessment of a course of this nature, the retrospective questionnaire was developed to address course design and learning outcomes as explicitly and specifically as possible. While aiming to improve accuracy of the survey, this limits the generalizability of the instrument. Additionally, and as indicated by student feedback in Table 3, there is ample opportunity for refining and improving this relatively new course to leverage potential learning benefits of interdisciplinarity. Despite these limitations and opportunities for improvement, these results are consistent with preliminary realization of the educational benefits and positive student response to an interdisciplinary chemistry course.

CONCLUSION

As the increasing complexity of science is juxtaposed against growing public interest and politicization of issues involving science, students will benefit from educational initiatives that transcend traditional disciplinary boundaries. These initiatives should be designed to help students achieve higher order learning objectives, including problem solving skills, developing new perspectives, and applying information to better understand complex problems. Student feedback received for the interdisciplinary course The Chemistry of Poisons indicated the achievement of higher order learning objectives. Practical challenges to the development and implementation of interdisciplinary courses and activities, such as which content to include and how it should be sequenced, necessitate ongoing development and experimentation in content delivery and assessment of associated learning objectives. The instructors should share enough background and expertise to facilitate effective collaboration, while also holding distinct specializations, to maximize the team's ability draw from multiple disciplines. As the "central science," chemistry is a discipline that is intrinsically well-suited for this aim, a claim corroborated by the variety of unique examples of interdisciplinary courses and activities that have been developed and described in the literature. The Chemistry of Poisons is a course that demonstrates the potential advantages of interdisciplinary education, as indicated by student interest and feedback. This course is an excellent example of innovative, student-centered education that we hope will provide a strong foundation for new academic initiatives geared toward delivering chemical, pharmacological, and humanistic content in a manner that is enjoyable for students and demonstrably facilitates knowledge and application level learning.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

Instructor reflections, complete student survey results, analysis of survey results

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