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Article

Design of a Drug Discovery Course for Non-Science Majors[S]

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Abstract

"Drug Discovery" is a 13-week lecture and laboratory-based course that was developed to introduce non-science majors to foundational chemistry and biochemistry concepts as they relate to the unifying theme of drug discovery. The first part of this course strives to build students' understanding of molecules, their properties, the differences that enable them to be separated from one another, and their abilities to bind to biological receptors and elicit physiological effects. After building students' molecular worldview, the course then focuses on four classes of drugs: antimicrobials, drugs that affect the mind, steroid-based drugs, and anti-cancer drugs. During each of these modules, an emphasis is placed on how understanding the basis of disease and molecular-level interactions empowers us to identify novel medicinal compounds. Periodic in class discussions based on articles pertinent to class topics ranging from the spread of antibiotic resistance, to the molecular basis of addiction, to rational drug design, are held to enable students to relate course material to pressing problems of national and daily concern. In addition to class time, weekly inquiry-based laboratories allow students to critically analyze data related to course concepts, and later in the semester give students an opportunity to design and implement their own experiments to screen for antimicrobial activity. This course provides students with an understanding of the importance of chemistry and biochemistry to human health while emphasizing the process, strategies, and challenges related to drug discovery. © 2018 by The International Union of Biochemistry and Molecular Biology, 46:327–335, 2018.

Keywords: *Drug discovery; inquiry-based; first-year undergraduate; hands-on learning; non-major courses; interdisciplinary*

Theme-based courses for teaching chemistry and biochemistry to non-science majors are an increasingly popular means of conveying foundational concepts to a general audience that is unlikely to continue in the field. Though there is a tradeoff between breadth and depth in theme-based non-science majors courses versus traditional introductory courses, theme-based courses benefit from linking the process and products of science to pressing societal issues, ultimately providing a platform for lasting impact. Recent papers have described successful theme-based courses focused on food chemistry [1, 2], forensics [3, 4], scents [5], and environmental chemistry [6], for example. Each of these topics offers a unique and creative opportunity to analyze chemistry in context while creating a venue that promotes student engagement [5]. Given the pervasive role that chemistry and biochemistry play in pharmaceutical development and the positive impact that biochemists have on human health in this arena, a theme-based non-science majors course on drug discovery should be a broadly appealing addition to this repertoire. Though the educational literature describes courses that present drug discovery at an advanced level (e.g. Medicinal Chemistry, Pharmaceutical Chemistry) [7–9], to the best of my knowledge the only literature describing a non-science major course on this topic is focused on drug action in a lecture-only class [10]. Gaining a molecular-level understanding of drugs, their isolation, and their interactions with biological receptors requires topics traditionally introduced in general chemistry, organic chemistry, and biochemistry, whereas understanding their mechanism of action relies on understanding normal versus disease processes in biological

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systems and thus requires content covered in biology courses. The interdisciplinary nature of the field of drug discovery gives non-majors courses in this area the potential for exquisite tailoring.

In addition to offering a unifying theme for covering chemistry and biochemistry concepts in the classroom, the drug discovery theme is rife with possibilities for inquiry-based laboratories. Previously described laboratory-based activities, including molecular modeling of pharmaceuticals [11, 12], thin-layer chromatography-based analysis of analgesics [13, 14], chemical synthesis of aspirin [15], screening of molecules for antimicrobial activity [16, 17], and computer-aided drug design [18], fit seamlessly under the drug discovery umbrella. Further, drug discovery is a multidisciplinary topic that has connections to the history of scientific thought, the sociology of access to healthcare, the neuroscience of drug addiction, the public health impacts of antibiotic resistance, the economics of drug pricing, the laws behind patent protection, and the government oversight of pharmaceuticals, on top of the underpinning chemistry and biochemistry concepts. Therefore, important connections to everyday, cross-disciplinary issues are possible.

This article describes the design of a non-science majors Drug Discovery course along with accompanying laboratory activities. Based on assessment data from three iterations of this course for non-science majors at Bowdoin College, this course appears to effectively meet its learning objectives while maintaining high enthusiasm among course participants.

Course Description

The goal of this one-semester "Drug Discovery" course is to introduce non-science majors to foundational chemistry and biochemistry concepts as they relate to the unifying theme of drug discovery, ultimately enhancing the scientific literacy of these students. Toward achieving this broad goal, the following learning objectives were set: (1) build a molecular understanding of drugs, drug-receptor binding, and drug action, (2) pose and test hypotheses related to drug discovery and drug action, (3) critically analyze data and make scientifically-sound conclusions, (4) evaluate the current approaches to drug discovery, and (5) convey scientific information in a coherent, accessible, and scientifically accurate manner. The assignments and laboratories in this course were designed to help students meet these objectives while providing opportunities for assessment of student learning outcomes.

The course consists of a brief introductory unit on the history of drug discovery, a month-long unit on building a molecular worldview, applied case study units on (1) antimicrobials, (2) drugs that affect the mind, (3) steroid-based drugs, and (4) anti-cancer drugs, and a big-picture conclusion unit on approaches to drug discovery. The concepts covered as well as laboratory experiments associated with each unit are provided in Table I. The introduction unit motivates the arc of the course by putting the evolution of systematic medicine and drug discovery into context. An intensive unit on building a molecular worldview familiarizes students with atoms, chemical bonding, and chemical structure, launches into how polarity impacts intermolecular forces and the properties of molecules, covers how these properties enable molecules to be separated from one another, and describes how shape and chemical complementarity underpin the binding of molecules to biological receptors. The applied case studies describe the molecular basis of different types of disease and how understanding the molecular basis of disease enables systematic drug discovery (Fig. 1). Finally, course concepts are pulled together in a unit focused broadly on approaches to drug discovery.

In parallel to learning about concepts in class, students perform weekly inquiry-based laboratories that are designed to reinforce their molecular worldview. For example, students employ molecular models to explore what molecules look like in three dimensions, perform thin layer chromatography to evaluate how molecules can be separated from one another [14], and evaluate how a tea alters taste perception via a molecule that binds and blocks a taste receptor [19]. Later in the semester, students embark upon a multi-week "research-like" project laboratory, in which they design and implement their own experiments to search for antimicrobials.

Course Design

Drug Discovery is a general audience course that was developed to meet the "Inquiry in the Natural Sciences" distribution requirement at Bowdoin College. This course primarily serves first and second year students who are eager to fulfill their distribution requirements, though any student who has not taken introductory chemistry may enroll. The course draws students across myriad majors, including history, government, economics, sociology, psychology, and music. During the 13-week semester, the course meets three-times per week for class periods (55 min each) and once a week for laboratory (90 min), which periodically doubles as a time to give exams lengthier than the class period allows. Class size is limited to 25 students due to laboratory space constraints.

The primary teaching methods in class are lecture, problem solving, and discussion. For problem solving exercises, the think-pair-share model is employed to encourage active learning and collaboration. Periodic discussions are held that focus on *Scientific American* articles pertinent to class topics, ranging from the spread of antibiotic resistance [20, 21], to the molecular basis of addiction [22, 31], to rational drug design [23]. For laboratory activities, students work in pairs for experiments, but they turn in individual laboratory worksheets and reports. There is no

TABLE I ***Drug Discovery Schedule with lesson modules, concepts, and laboratory activities***

Week	*Lesson modules*	*Concepts*	*Laboratory activities*
1	Curing diseases: the early days	Evolution of thought about cause of diseases and how to treat them; key steps that helped systematize medicine	None
2	Building a molecular worldview	Atoms; electrons; molecules; bonding; Lewis dot structures; structural formulas; skeletal structures	Seeing molecules in three dimensions
3	Separating compounds based on their properties	Electronegativity; polarity; intermolecular forces; "like dissolves like"; extraction, chromatography	Analysis of pain-relieving medications by TLC
4	Drug-receptor binding	Shape and chemical complementarity; chirality; importance of correct "handedness" for eliciting desired biological activity	Effects of drug-receptor binding: altering taste
5	Antimicrobials: germ theory of disease	Germ theory of disease; pasteurization; Koch's postulates; antiseptic surgery; power of understanding the basis of disease	Exam I
6	Antimicrobials: antibacterials	"Magic bullet"; penicillin discovery; zone of inhibition; Kirby-Bauer disk-diffusion assay; activity-guided fractionation	Antimicrobials: design experiment
7	Antimicrobials: antibiotic resistance	Selection of antibiotic resistance; molecular basis of resistance; overcoming antibiotic resistance	Antimicrobials: perform experiment
8	How the mind works: neurotransmission	Synaptic transmission is mediated by neurotransmitters; structural classes of natural neurotransmitters	Exam II
9	Drugs that affect the mind: from morphine to prozac	Mechanisms by which neuroactive drugs act; molecular basis of addiction; fighting addiction	Antimicrobials: present results; plan next steps
10	Steroid-based drugs: from cortisone to the pill	Understanding the biology of steroids (testosterone, estrogen, progesterone) has enabled the development of steroidal drugs	Antimicrobials II; perform follow-up experiments
11	The molecular basis of cancer and its causes	Hallmarks of cancer; mutations in DNA; role of chemicals, radiation, genetics and time in causing DNA mutations	None (Thanksgiving)
12	Anti-cancer drugs	Traditional vs. "targeted" chemotherapeutics; antibody-based chemotherapies; resistance to anticancer drugs	Antimicrobials II: present final results
13	Approaches to drug discovery	Rational design; combinatorial chemistry and library-based approaches; ethnobotany	Final Exam

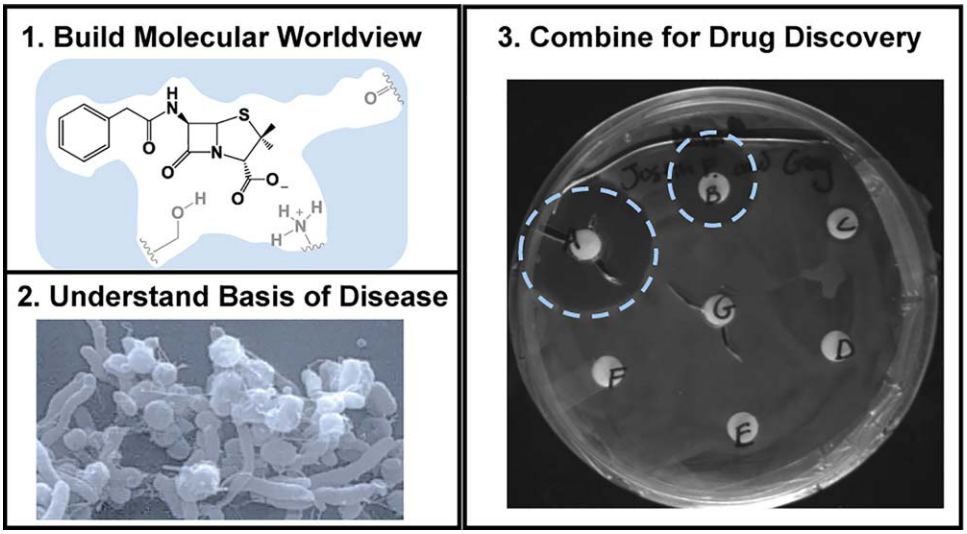

FIG 1 *The conceptual framework for the Drug Discovery course relies on first building a molecular worldview, then understanding the molecular basis of disease, and finally combining this knowledge to enable drug discovery. [Color figure can be viewed at wileyonlinelibrary.com]*

textbook that captures course topics at an appropriate level, so a course reader is used that contains chapters culled from general chemistry, introductory biology, and microbiology texts. Supplemental readings are assigned from *Napoleon's Buttons: How 17 Molecules Changed History* by Penny LeCouteur & Jay Burreson [24] and *Laughing Gas, Viagra, and Lipitor: The Human Stories Behind the Drugs We Use* by Jie Jack Li [25].

Course Content

Week 1: Brief History of Drug Discovery

The course begins with a brief survey of the history of drug discovery, starting with evidence of drug use in pre-historic times and moving briskly through a timeline highlighting the evolution of scientific thought as it relates to disease treatment. Key points are stressed along the way, including myriad approaches to treating disease (e.g. incantations, medicinals, bloodletting), viewpoints on the basis of disease (e.g. an imbalance in the four humors), strides to systematize the use of medicinals (description of herbals in *De Materia Medica*), observations about proper dosage, philosophies regarding monopharmy versus polypharmy, evidence of successful therapies, and the "first" clinical trial aboard the HMS Salisbury [26]. The timeline ends at the beginning of the modern era of scientific discovery, with the observation that tree bark contains many components, and that isolated components are the active principles that prompt medicinal effects [26]. The goals of this introductory unit are to convey that scientific thought evolves over time and to motivate students to build their molecular worldview so that they can understand what active principles are, how they can be isolated, and how they elicit a biological effect to enhance human health. No laboratory is offered during this unit.

Weeks 2–4: Building a Molecular Worldview

This unit focuses on foundational chemical concepts that students use throughout the semester. Atoms are introduced as molecular building blocks that, based on their placement in the periodic table and their number of valence electrons, have tendencies to gain, lose or share electrons. The Lewis model of bonding is then introduced as a means for atoms with complementary tendencies to become more stable or "satisfied." Students are introduced to Lewis dot structures, structural formulas, and skeletal formulas, and they perform an exploratory laboratory activity with molecular model kits to understand valence shell electron-pair repulsion theory and see that many molecules are not flat (see Supporting Information). Focus is placed dominantly on the most common elements found in living organisms and in therapeutics (e.g. C, H, N, O, S).

Once students are familiar with molecules and their composition, the concept of electronegativity is presented and transitions smoothly to topics including polarity, intermolecular forces, and solubility. These concepts in turn segue into how these properties can be taken advantage to separate molecules from one another via extraction and chromatography. In a corresponding laboratory activity, students perform extractions and thin layer chromatography analyses to ascertain what components are present within unknown over-the-counter analgesics (see Supporting Information) [13, 14].

This unit then transitions to the concept of biological receptors and, using a traditional lock-and-key model, the requirement that molecules bind to receptors that have both shape and chemical complementarity. The notion of

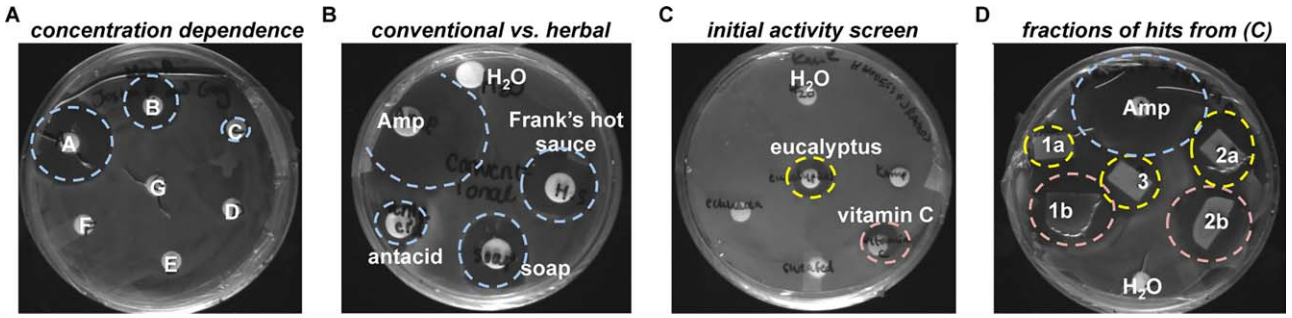

FIG 2

Sample student data from antimicrobials project laboratory. (A) Students assessed the concentration-dependence of ampicillin (Amp) at inhibiting the growth of ampicillin-sensitive Escherichia coli*; serial 10-fold dilutions of an ampicillin stock solution were placed on disks A through G. (B) The antibacterial activities of conventional versus herbal remedies were compared and revealed that Frank's hot sauce inhibits* E. coli *growth. (C) In an initial antimicrobial activity screen, one group of students found that the herbal supplements eucalyptus oil and vitamin C exhibited antibacterial activity. (D) In follow-up experiments based on the data shown in (C), students performed thin layer chromatography to separate compounds found in eucalyptus oil (fractions 1a, 2a, 3) and vitamin C (1b, 2b) and assessed the activity of these fractions relative to controls. For the experiment shown in D, TLC-resolved fractions were cut out of plastic-backed TLC plates and placed silica-side down directly on the inoculated agar plate. [Color figure can be viewed at wileyonlinelibrary.com]*

chirality, its importance in eliciting desired biological activity, and case studies describing the effects of racemic drugs are also covered. For this final part of the molecular worldview unit, students perform a laboratory activity based on *Gymnema sylvestre* tea and explore the effect *Gymnema* tea has on taste perception [19]. Crucially, the effect of the tea is explored by considering what molecular receptors might look like for different tastants (e.g. Na^+, glucose, umami) and how gymnemic acid, the active principle in *Gymnena* tea, might bind to these hypothetical receptors (see laboratory worksheet in Supporting Information).

Weeks 5–7: Antimicrobials

After building a chemical understanding of drugs, the course launches into its first and most intensive case study on antimicrobials. This unit begins with the germ theory of disease, evidence that supports this theory, and proof required to establish that a particular microorganism causes a disease. Then, the development of antimicrobials is discussed. Examples range from Joseph Lister's deployment of phenol for antiseptic surgery, to the development of more selective drugs based on Erlich's "magic bullet" hypothesis, to the benefits of *in vivo* screening to yield sulfa drugs, to Alexander Graham Fleming's serendipitous discovery of antimicrobial activity by penicillium mold. Key to these examples is the process of discovery, the steps taken to follow up on lead compounds, and the molecular mechanism of antimicrobial activity for the discovered therapeutics. The importance of systematic screening for desired activity is described. These examples arm students with the ability to design activity-guided fractionation experiments to isolate active antimicrobials from a mixture.

Once successes in the discovery and development of antibiotics are described, this unit then takes a turn to investigate a problem that plagues the field: antibiotic resistance. The concepts covered here include the selection of antibiotic resistance, the molecular basis of resistance (e.g. mutated receptor, efflux pump, inactivation of antibiotic), and approaches that chemists take to tackle antibiotic resistance (e.g. second generation antibiotics). Vibrant discussions are held based on *Scientific American* articles [20], and students consider different ways to tackle the challenge of antibiotic resistance [21]. To add an extra layer of complexity to the antimicrobials conversation and incorporate cutting-edge topics, we also discuss the presence of beneficial microorganisms in our bodies and the unintended harm that broad-spectrum antibiotics can cause [27, 28].

Weeks 6–12: Antimicrobials Project Laboratory

A highly successful component of the course is the antimicrobials laboratory, in which students are challenged to practice the scientific method to either identify novel therapeutics or to directly compare conventional versus herbal remedies. This multi-week laboratory was inspired by laboratory experiments that offer "research-like" experiences for students [29]. The antimicrobials project laboratory is intended to provide students with an understanding of the trials and tribulations associated with research while at the same time giving them the thrill of discovery, as well as sense of ownership, that comes along with designing and implementing experiments. Indeed, research-like experiences in other courses have a high impact on learning outcomes. There is overlap between class and laboratory content at the start of this laboratory sequence, but the lab ultimately diverges from the rest of the topics covered in the course to provide ample time for an in-depth research-like experience.

In the initial antimicrobials laboratory module (week 6), students pair off and pose a hypothesis about which chemicals they expect to have antimicrobial activity. After they select compounds or substances to test, they design an

experiment to test these materials for antimicrobial activity (either anti-bacterial, anti-fungal, or both) using a Kirby-Bauer disk-diffusion assay [30]. Guidance from a worksheet includes suggested phrasing for posing hypotheses, information about materials available in the laboratory, and types of controls that should be included, all of which prompt brainstorming and facilitate experimental design (see Supporting Information). In addition to designing the experiment, students also depict their expected results on a worksheet to help them consider what they might see if their hypotheses are correct (see Supporting Information). During the next laboratory period (week 7), following a short demonstration, they perform experiments to test for antimicrobial activity. The next day they collect their data, which they then discuss and analyze in lab during week 9. This cycle is then repeated to enable students to track leads or to modify their hypotheses. In the second antimicrobials laboratory cycle, students plan (week 9) and conduct (week 10) follow-up experiments in response to their initial results. The antimicrobials laboratory concludes with students discussing and presenting their final results (week 12), as well as turning in a final laboratory worksheet.

This project laboratory enables students to pose and test a range of hypotheses. For example, Drug Discovery students have confirmed that the amount of antibiotic used correlates with its activity (Fig. 2A), Frank's Hot Sauce is a potent antibacterial (Fig. 2B), and eucalyptus oil and vitamin C effectively kill kanamycin-resistant *Escherichia coli* (Fig. 2C). Follow-up experiments have included activity-guided fractionation (e.g. hydrophilic versus hydrophobic extracts; spots resolved by TLC) of bioactive material discovered in the first laboratory (Fig. 2D), testing known components from bioactive substances for activity (e.g. testing the principle component of garlic, allicin, after garlic demonstrated antibacterial activity), ascertaining whether "hits" are narrow-spectrum versus broad-spectrum by testing for activity against a range of bacterial strains, and determining the minimum concentration of FDA-approved antibiotic needed to kill antibiotic-sensitive versus antibiotic-resistant strains of *E. coli*. These laboratories empower students to conceive of their own projects, design experiments to test their hypotheses, and personally contribute to research.

Weeks 8–9: Drugs That Affect the Mind

The second case study unit focuses on neuroactive drugs. This unit begins with a primer on neurons and synapses, covers the "soups versus sparks" debate and Otto Loewi's famous experiments revealing the critical role of molecules in synaptic transmission, and develops a model of synaptic transmission mediated by neurotransmitters binding to neurotransmitter receptors. Once a conceptual model of "normal" neuronal function is presented, students brainstorm and suggest mechanisms by which drugs might alter neuronal function. Structural classes of natural neurotransmitters and their physiological effects are presented, along with neuroactive drugs that alter neuronal signaling by causing a signal in the absence of input or preventing a signal in the presence of input. This topic dovetails with a problem endemic in society—addiction. Therefore, articles focused on the molecular basis of addiction and approaches to fighting addiction are discussed [22, 31].

Week 10: Steroid-Based Drugs

The third case study unit covers the discovery of key sex steroids (testosterone, estrogen, progesterone), experiments performed to discover their physiological effects [32], the molecular basis for their effects, and the use of steroids and steroid analogs that block or activate steroid receptors to treat diseases (e.g. cancer, muscle atrophy) and develop contraceptives. In essence, this unit conveys that understanding the biology of steroids has enabled the development of steroidal drugs. An in class discussion focused on environmental estrogens is incorporated to connect class material to environmental issues [33, 34].

Weeks 11–12: Anti-Cancer Drugs

The final case study covered focuses on anti-cancer drugs. This unit begins with the six hallmarks of cancer and describes how cancer is a disease in which normal processes become dysregulated [35]. Once the hallmarks of cancer are described, the concept that these hallmarks are acquired by the accumulation of deleterious mutations in the DNA of malignant cells is introduced. Causes of cancer, such as carcinogenic chemicals, ultraviolet and X-ray radiation, some viruses and bacteria, certain hereditary genes, and even age, and how each one of these causes is linked to the acquisition of genetic mutations, is presented. Finally, with an understanding of the molecular basis of cancer, the focus shifts to how to fight cancer via traditional and new, targeted approaches. The role of biologics such as monoclonal antibodies in the fight against cancer is introduced, as well as debates about drug pricing given the steep cost of these therapies. This unit has strong connections to concepts introduced in the antimicrobials unit, such as Koch's postulates, evolution of resistance, and overcoming resistance mechanisms.

Week 13: Approaches to Drug Discovery

The course concludes with stepping back and analyzing different approaches to drug discovery, including rational design [23], combinatorial chemistry [36], and ethnobotany [37]. The benefits and challenges of these approaches are compared, as is the value of having a multi-pronged approach to drug discovery. The timescale of the drug development process is covered, with an emphasis on the tremendous amount of time, effort, money, and failure associated with drug discovery. The course ends with a vignette about the future of drug discovery (e.g. personalized medicine) and a reminder that the field is continuously evolving.

TABLE II *Percentage student achievement of course learning objectives*

Learning objective	*Assessment mechanism*	*Student achievement*[a]
1. Build a molecular understanding of drugs, drug-receptor binding, and drug action	Exams	33% mastery, 40% above average, 19% satisfactory
2. Pose and test hypotheses related to drug discovery and drug action	Laboratory	100% met this objective
3. Critically analyze data and make scientifically-sound conclusions	Laboratory worksheets	94% met this criteria
4. Evaluate the current approaches to drug discovery	–	Not assessed
5. Convey scientific information in a coherent, accessible, and scientifically accurate manner	Exams, laboratory worksheets, and presentations	85% met threshold for proficiency

[a]*Based on 51 students.*

Laboratory Hazards

Three of the weekly laboratory activities (TLC of analgesics and the two antimicrobials experiment days) require laboratory space with fume hoods and bench space. During the wet laboratories, students are required to wear gloves and safety glasses. The wet laboratories utilize a variety of chemicals as well as Biosafety Level 1 organisms in the antimicrobials experiments. Students are alerted to chemical and biological hazards and instructed in safe handling and disposal.

Student Assessment

Students were assessed by weekly problem sets (15%), reading responses and participation (10%), two midterm exams (40%), a final exam (20%), and laboratory work (15%), which included completed laboratory worksheets and reports. Comprehension of course material was assessed via performance on the problem sets and exams. For laboratory work, for most activities students were given a laboratory worksheet at the beginning of each laboratory and turned in completed worksheets at the end of the laboratory (see Supporting Information). These short laboratory worksheets link to course material and provide an opportunity for students to tie concepts together more broadly. The antimicrobials laboratory worksheets are more extensive than the others and require effort outside of the laboratory period. Students turn in their completed laboratory worksheets, including their hypothesis, experimental design, predicted data, actual data, conclusions, and a discussion of their results in the context of previous research, their hypothesis, and future directions, the week following antimicrobials experiments (see Supporting Information).

Evaluation of the Course

The success of this course at meeting learning objectives was assessed via a variety of mechanisms, including performance on exams, in the laboratory, on laboratory worksheets, and during class presentations of antimicrobials laboratory results. On the basis of three iterations of the course and 51 students total, the vast majority of students met the stated learning objectives (Table II). Students performed particularly well with testing hypotheses and analyzing data (objectives 2 and 3). Accurately conveying scientific information (objective 4) is an area that could use improvement, though even with this learning objective 85% of students met the goal. Most critically, based on performance on exams, 92% of students achieved a satisfactory or better understanding of foundational molecular concepts (objective 1) that were used throughout the semester.

Student feedback on mid-semester evaluations and end-of-semester student opinion forms was very positive, with the contribution of this course to students' education scoring an average of 4.6 ± 0.1 (with 1 being "very little" and 5 being "very much") in end-of-semester evaluations.

When asked in mid-semester evaluations whether they would recommend this class to their peers, 100% of students who responded to the survey ($n = 48$) answered yes. Student comments indicated that the course covered "practical, real-world science" at "a perfect level for non-majors," and stated that the material was "extremely accessible and interesting." The laboratory activities were described as "welcome hands-on experiences," with comments including "Love the labs! They are super-interesting, and always connect to class. (And they're fun)!" Moreover, this class met the broad goal of engaging non-science students, with students noting "My appreciation for the sciences has grown significantly," and, among my favorites, "This course was AMAZING! I hated science—hated it—and now I really like it. I learned SO much!" Based on assessment and student feedback, this course met the learning outcomes for most students while keeping them engaged and enthusiastic.

Avenues for Modification

This course could be adopted as described, or it could be adapted to meet the needs of different institutions, course structures, and instructor styles. As described, the course is designed to fit a 13-week semester schedule. To adapt this course to shorter time frames, such as those found in the quarter system, the introductory units covered in weeks 1–4 could be coupled to a selection of two of the four case study units. For example, introductory material, antimicrobials, and anti-cancer drugs, coupled to the laboratories described, tie together conceptually and would fit seamlessly into a stand-alone 10-week class. Though the laboratory exercises enhance the student experience and student learning outcomes, if space or resource limitations preclude the inclusion of a weekly laboratory, the course could be offered without the laboratory. Conversely, the antimicrobials laboratory can be decoupled from the course. I have offered a two-day antimicrobials laboratory to incoming first year students as part of the "Bowdoin Science Experience" orientation program. In the two-day short course, students design and perform antimicrobial experiments on the first day, then analyze data, consider possible future directions, and discuss the challenges of antimicrobial resistance on the second day. Even a brief exposure to the discovery process generates an enthusiastic reaction from students.

Given the breadth of the field of Drug Discovery, there are ample opportunities for course instructors to modify the content, select different case studies, and connect material more broadly to societal and economic challenges. Assigning research papers or presentations, in which students learn about a particular area of drug discovery in-depth and then describe their findings, could incorporate additional elements of discovery that are tailored to student interests. Alternative laboratory exercises could be incorporated, including activities focused on neurophysiology [38, 39], isolating an antidepressant from St. John's Wart [40], removal of environmental estrogens from contaminated water [41], and synthesis of an anti-cancer drug [42]. Thus, though one model for a course on Drug Discovery is presented, this course can be tailored to suit the instructor, institution, and student body.

Conclusion

In summary, a successful semester-long Drug Discovery course for non-science majors is described. The drug discovery theme provides a context for introducing chemistry and biochemistry concepts, as well as for tying the material to broader societal challenges. The course includes a series of inquiry-based laboratories, including one multi-week unit on antimicrobial screening, in which students have an opportunity to master course concepts and gain familiarity with scientific exploration. On the basis of instructor and student assessment, this course effectively meets its learning objectives while maintaining high enthusiasm among course participants.

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