JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

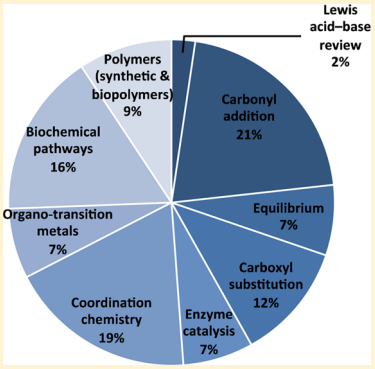
Reactivity I: A Foundation-Level Course for Both Majors and Nonmajors in Integrated Organic, Inorganic, and Biochemistry

Chris P. Schaller,* Kate J. Graham, Brian J. Johnson, T. Nicholas Jones, and Edward J. McIntee

Chemistry Department, College of Saint Benedict/Saint John's University, Ardolf Science Center, 37 South College Avenue, St. Joseph, Minnesota 56374, United States

Supporting Information

ABSTRACT: A foundation level course is presented that integrates aspects of organic, inorganic and biochemistry in the context of reactivity. The course was designed to serve majors in chemistry and other sciences (biochemistry, biology, nutrition), as well as nursing and pre-health professions students. Themes of the course were designed to highlight a range of applications of chemistry, including synthesis, catalysis, and materials science, in order to teach students the wider societal significance of chemistry, in addition to chemical concepts. Special attention was paid to topics relevant to health and biology.



KEYWORDS: *First-Year Undergraduate/General, Biochemistry, Curriculum, Inorganic Chemistry, Organic Chemistry, Inquiry-Based/Discovery Learning, Bioorganic Chemistry, Coordination Compounds, Metabolism, Catalysis*

INTRODUCTION

Relatively little has changed in the sequence of courses taken by chemistry majors over the past 50 years.[1] The series starts with a year of general chemistry, including a heavy emphasis on concepts of physical and analytical chemistry. A year of organic chemistry comes next, followed by varying amounts of analytical and physical chemistry. If the student is an ACS chemistry major, they also take some amount of inorganic and biochemistry.

The recent revision of guidelines from the American Chemical Society Committee on Professional Training (ACS-CPT) has allowed for some degree of innovation in the structure of chemistry programs.[2] The guidelines recommend "foundation-level" instruction in each of five traditional domains of chemistry (organic, inorganic, physical, analytical, and biochemistry) plus some coverage of a sixth (polymer chemistry). Additional "in-depth" courses allow students to explore these domains further, either in more advanced treatments of the foundation topics or in special topics courses. General chemistry is not explicitly included in the new ACS guidelines; it is considered prefoundational and its delivery is left to the discretion of individual departments.

Many departments will continue to offer the old curriculum. However, others will be interested in new variations. Some may be drawn to provide interdisciplinary approaches that fit their unique situations, especially if strong institutional ties exist with other disciplines. More broadly, recent trends in research and industry have increased the pressure for chemists to integrate skills from different traditional domains of chemistry.[3] Educational changes outside of chemistry, most notably in the premedical curriculum, have also contributed to a reevaluation of how to serve those not majoring in chemistry.[4−6]

Recently, an alternative organization of the chemistry curriculum was proposed based on courses in structure, reactivity, and quantitation.[7] Structure includes a range of considerations such as periodic trends, unit cells in extended solids, stereochemistry, and conformation.[8] Reactivity includes the prediction of reactions and understanding of mechanisms across organic, inorganic, and biochemistry. Quantitation encompasses the usual considerations of physical and analytical chemistry. Other suggestions for the reorganization of the chemistry curriculum have also been made, although along different lines.[9,10] The chemistry curriculum of the 21st century should be based on earnest consideration of a range of options rather than the convenience of maintaining the *status quo*.

Interest in developing hybrid approaches to traditional chemistry courses has circulated for years. Several authors have reported an early introduction to organic chemistry, either in the first semester of the first year (eliminating general chemistry)[11−13] or in the second semester of the first year (a 1:2:1 approach).[14,15] Others have integrated organic and general chemistry content across two years.[16,17] Similarly, the study of organic chemistry has been leavened with varying amounts of biochemistry or bioorganic chemistry.[18−20] Although these changes have been driven by a number of motivations, a key impetus has been to bring a relevant context

Published: September 18, 2015

DOI: 10.1021/acs.jchemed.5b00103
J. Chem. Educ. 2015, 92, 2067−2073

Table 1. Foundation-Level Chemistry Courses at CSB/SJU

Course (Semester)	Emphasis
Chem 125: Structure and Properties (1st)[a]	Atoms, solids, molecules, geometry, stereochemistry, intermolecular attraction, acid−base
Chem 250: Reactivity I (2nd)	Basic equilibrium, carbonyl chemistry, coordination compounds, metabolic pathways
Chem 251: Reactivity II (3rd)	Kinetics, enzyme inhibition, aliphatic substitution, alkene addition, arene substitution, organometallics
Chem 255: Macroscopic Analysis (4th or 5th)[b]	Quantitative thermodynamics, equilibria, electrochemistry, statistics
Chem 315: Reactivity III (4th or 5th)[b]	Redox, radicals, oxidative phosphorylation, photochemistry, photosynthesis, pericyclics
Chem 318: Microscopic Analysis (5th or 6th)	Quantum chemistry, spectroscopy,

[a]Prefoundational, equivalent to a general chemistry course. [b]Often taken concurrently by majors.

for the study of chemistry to the large number of biology, biochemistry, and pre-health professions majors served by introductory courses. Context has been demonstrated to be a crucial factor to foster student engagement in course material.[21] Changes in the organic curriculum have also been driven by a continuing desire to develop an improved storyline in terms of mechanism.[22] However, there are few choices of organic chemistry textbooks that support these approaches.[23]

Less attention has been paid to inorganic chemistry at the introductory level. The subject has been used as a way to energize first-year studies by presenting students with material they have not seen in high school.[24] In addition, a second-year organometallics course has been described previously.[25] However, connections between inorganic and organic or biochemistry could be explored further in an introductory course. These ties might be exploited to increase understanding of both areas. For example, the use of traditionally organic arrow-pushing conventions has been exploited to generate greater student engagement in advanced inorganic chemistry.[26] Of course, the crucial role of metal ions in biology and organic chemistry is undisputed.[27]

An emphasis on the commonality between organic, inorganic, and biochemistry provides multiple access points to chemistry for students with a range of interests. In addition, it may help the development of key concepts of chemistry. Students need to make gradual progress toward an understanding of particulate concepts of matter. An early introduction to these concepts enables extended revision of their ideas, allowing students to approach a more acceptable understanding of the material.[28]

In response to the ACS-CPT guidelines for "foundation-level" instruction, the curriculum was revised (Table 1). Herein, the first course (Chem 250) of three courses (Chem 250, 251, 315) is described that provides integrated coverage of introductory reactivity in organic, inorganic, and biochemistry. This lecture course has been taught since spring, 2012. A loosely affiliated laboratory course will be described elsewhere in detail, although a general outline has already been communicated.[7]

THEORETICAL FRAMEWORK CHEM 250

Chem 250: Reactivity I was designed with the guiding principles of Novak's theory of meaningful learning.[29] As much as possible, new information is related to previous concepts, so that learning is built up from a stronger network of ideas. New topics are frequently introduced with stories about chemical processes that are relevant to everyday life, allowing students to place ideas more easily in a significant and easily recalled context. Topics are brought back in different contexts at later stages of the course, presenting students with an opportunity for "integrative reconciliation" in which previous errors in thinking can be recognized and corrected when models are applied in different situations.[30] The goal of this approach is to enable students to apply their learning by transferring their understanding to new and unfamiliar information.

CONTEXT OF THE COURSE

The course is taught at a relatively large liberal arts college (over 3500 students on two campuses, linked by a bus service). Nevertheless, class sizes are small (fewer than 30 students in a section for a foundation-level chemistry class). The emphasis on breadth of education in a liberal arts environment is not consistent with specialized introductory courses for chemistry majors only, so Chem 250 is meant to serve majors in chemistry, biochemistry, biology, and nutrition, as well as pre-health professional students.

Prior to introducing the new curriculum, it was part of the culture to innovate with course design based on student performance. For example, in organic chemistry, a spectroscopy-first approach had been in use for at least 15 years, and an early introduction to carbonyls for about 10. Short modules had previously been used on bioorganic and organometallic chemistry,[31] as well. These developments made it easier to transition to a new curriculum, but complicate assessment of the change.

The prerequisite course to Chem 250 is Chem 125: Structure and Properties in Chemistry, a one-semester overview of structural considerations in chemistry.[8] Chem 250 is the first foundational course in chemistry. After Chem 250, students take a second, complementary course, Chem 251: Reactivity II. Quantitative aspects of chemistry are then introduced in Chem 255: Macroscopic Analysis. Both chemistry and biochemistry majors, as well as most pre-health professions students, take these four courses in their first two years. This course sequence is similar to a 1:2:1 curriculum with an early, two-semester introduction to organic chemistry followed by a semester of quantitative chemistry. However, Chem 250 differs significantly from first-semester organic chemistry in that a large fraction of the content would traditionally be described as inorganic chemistry. Another major portion is biochemistry, an innovation that has been introduced in some other curricula. Although it does not reflect the practice at CSB/SJU, Chem 250 could be delivered as a second-year course after a traditional two-semester general chemistry sequence.

At CSB/SJU, students register for laboratories separately from lecture courses. This system has helped to improve flexibility of scheduling and accommodates certain departments, such as nutrition and nursing, that request chemistry courses without a laboratory component. This paper does not address questions regarding laboratory instruction.

OVERVIEW OF COURSE CONTENT

A list of topics covered in Chem 250 is presented in Table 2.

DOI: 10.1021/acs.jchemed.5b00103
J. Chem. Educ. 2015, 92, 2067−2073

Table 2. List of Topics in Chem 250: Reactivity I

Topic	Class Periods
Review of Lewis acids and bases	1
Addition to carbonyls (anionic, ylide and enolate nucleophile)	6
Enthalpy, entropy and equilibrium	3
Substitution at carboxylic acid derivatives (including enolates)	3
Substitution at sulfonate and phosphate	1
Conjugate addition	1
Catalysis and enzymes	3
Coordination Compounds	2
Ligand Field Theory	6
Carbonyl Binding and Organometallic Insertion	3
Reversible addition to carbonyls (neutral nucleophiles)	3
Mechanism: glycolysis, TCA cycle, fatty acids	3
Regulation: glycolysis, TCA cycle, fatty acids	4
Polymer synthesis and properties	2
Protein biosynthesis	2

Organic carbonyl chemistry was the first major topic, and its importance in mechanistic biochemistry provided inherent appeal particularly to pre-health, biochemistry and biology students. Anionic nucleophiles were addressed first, and students began to practice with concepts of electrophiles and nucleophiles, reaction intermediates, and electron flow during bond-making and bond-breaking steps.

After an initial exposure to reactivity, students explored some basic ideas about thermodynamics, including enthalpy, entropy, and free energy, as well as the concept of equilibrium and Le Chatelier's principle. The reversible formation of enolate ions provided a context for these ideas. Subsequently, interconversion between carboxylic acid derivatives offered an excellent platform for the discussion of driving force and energetically coupled reactions, a key concept in biochemical pathways.

A brief overview of catalysis served as an introduction into coordination chemistry. For example, the important role of metal ions to activate carbonyls toward electrophilic addition was stressed, as well as to activate water toward nucleophilic addition. The previous coverage of carbonyl additions also provided a doorway into transition metal organometallic reactions; analogies were drawn between migratory insertion reactions in organometallics and the addition of nucleophilic Grignard reagents and complex hydrides to organic carbonyls.

The addition of neutral nucleophiles to carbonyls was introduced before a discussion of metabolic pathways. The latter discussion included glycolysis, gluconeogenesis, the TCA cycle, and fatty acid metabolism. This section included a focus on mechanistic steps, as well as on regulatory events, including covalent modification and allosteric inhibition and activation. Details about regulation were discussed in the context of the thermodynamics of the pathways.

CLASSROOM ORGANIZATION

Activities in Chem 250 included a mixture of written homework assignments, online drill assignments, and quizzes of various lengths (see Supporting Information, section SI2). Active participation was also part of the course grade, assessed through instructor observation as well as peer evaluation.

Students in Chem 250 were provided with a daily schedule to help them keep track of resources and expectations (see Supporting Information, section SI3). The schedule outlined the readings that should be done before each class. To enforce preparation, the schedule may indicate a brief quiz at the beginning of class (via Socrative, but clickers and other tools could be used).[32] An online homework assignment may be due before class meets (via OWL or other platforms).[33] Students might also hand-in a homework assignment, either individually or in groups. Sometimes, a passport to class was due; typically, this was a 1−2 page preparatory assignment worth 2−5 points (less than 0.5% of the course grade) and quickly checked on a "plus/check/minus" basis (full points/half points/no points).[34]

The lecture period was interactive; there is a plethora of active learning methods from which to choose.[35] A Chem 250 class typically started with a short (∼5−10 min) lecture at the beginning of class, usually with shorter (∼5 min) recaps at the middle and end of the period. Students spent the remainder of the period (∼35−40 min) in groups studying problems in a workbook (see Supporting Information, section SI4). Classrooms were furnished with round tables, each seating 3−5 students, in order to facilitate cooperative work and discussion.

EXAMPLES OF TOPICAL COVERAGE

Introduction to Catalysis is a good example of the development of an individual topic because it illustrates some concepts from organic, inorganic, and biochemistry (see Supporting Information, sections SI3 and SI4). In AY '15, this topic was presented about a third of the way through the course following the addition of anionic nucleophiles to simple carbonyls, an introduction to thermodynamics, and substitution at carboxylic acid derivatives.

Introduction to Catalysis was covered over three class periods. In the first class period, in a passport to class, students drew analogies between mountain ranges and reaction barriers, with mountain passes representing alternative reaction pathways. In class, the instructor briefly reviewed the typical mechanism of substitution at a carboxylic acid derivative. Students then considered acid and base catalysis of ester hydrolysis. Catalysis was found to offer an alternative pathway with a greater number of steps than the original, although each catalytic step may be more easily accomplished. Halfway through class, the instructor introduced bond strengths as a way to assess the thermodynamic difference between an acid chloride and an ester. Students were then presented with a completely unrelated reaction, hydrogenation of an alkene, to consider the energetics of bond-making and bond-breaking in a new case.

In the second class period, students reviewed enzyme receptor theory, a concept from Chem 125, in a passport to class. In addition, an online homework set helped them review amino acids and proteins, also introduced in Chem 125. After a brief Socrative quiz on nucleophilic substitution of carboxylic acid derivatives, the instructor introduced the idea of approximation as an enzyme strategy. Students proceeded through examples that illustrated additional strategies (transition-state stabilization, distortion, acid−base catalysis, and group transfer catalysis). A subsequent homework assignment reinforced the formation of a Lewis acid/base complex as a key step in reduction catalyzed by alcohol dehydrogenase.

In the third class period, students were given a brief Socrative quiz on enzyme strategies. The instructor briefly reviewed the concept of transition state stabilization with the help of a reaction progress diagram (potential energy diagram). Afterward, students used their knowledge of enzyme strategies to consider the development of enzyme inhibitors. They were introduced to reversible and irreversible inhibitors, and were

DOI: 10.1021/acs.jchemed.5b00103
J. Chem. Educ. 2015, 92, 2067−2073

encouraged to consider transition-state analogues as possible pharmaceutical leads. Students then applied their ideas in extended problems involving acetylcholinesterase and HIV-1 protease. These problems examined case studies from various points of view, including enzyme strategies, inhibition type, organic synthesis of inhibitors, and reaction mechanism.

Some of these principles appeared again toward the end of the course in a section on biochemical pathways, briefly summarized here. The first class period of this section included an examination of the mechanisms of glycolysis, highlighting the roles of imine and enamine intermediates, and the need for activation of substrates, including ATP, by metal ions. Students supplied curved arrows to propose how one intermediate is transformed into another, provided missing intermediates in a mechanism, or drew out an entire step-by-step mechanism for different parts of the pathway. During the second class period, a similar approach was taken with the TCA cycle.

In the third class period, students looked at the thermodynamics of glycolysis. They revisited the idea of energetically coupled reactions, one downhill and the other uphill, in the context of carboxylic acid derivatives. They also considered the thermodynamics of substitution at new functional groups, a phosphodiester and a carboxylate−phosphate mixed anhydride, compared to other carboxylic acid derivatives. They made decisions about what steps may be subject to regulation and considered what steps might take different pathways in gluconeogenesis vs glycolysis. In the fourth class period, students looked at allosteric inhibition and activation, as well as post-translational covalent modification, especially phosphorylation and acetylation. They worked through exercises that posed questions about preferred conformations of small molecules before and after covalent modification; similar questions led them to conclude that metal ions can also play regulatory roles.

During the fifth and sixth class periods, students applied principles from the sections on glycolysis/TCA cycle to both catabolic and anabolic pathways of fatty acids. They worked through questions about mechanism as well as regulation. The seventh class period entailed a case study on ketogenesis and diabetes. In addition to mechanistic questions, students assessed different inhibitors of tyrosine phosphatase as potential treatments for diabetes. They also used what they had learned to fill in missing steps in the synthesis of an inhibitor.

INSTRUCTIONAL RESOURCES

Because the unique collection of course topics does not afford a broad selection of commercially available resources, a workbook was produced in-house for class use. The workbook (approximately 450 pages) includes sections that gradually developed the concepts of each topic, requiring students to provide short answers or illustrations based on previous knowledge or information provided at the beginning of lecture. In addition, application sections, which might be covered in class or assigned as homework, pushed students to consolidate learning by placing new concepts in a variety of scenarios.

Students also needed a place to read and review material before and after class. Custom publishing agreements initially allowed us to provide students with background reading on the topics of Reactivity I, selected from two different textbooks that together covered the material.[36,37] In addition, textbook access was available via the online homework site accessed via the custom publishing agreement.[38,39] Because of the mix of chapters from different sources, students occasionally encountered passages that assumed familiarity with a topic that had not been covered in class. Instructors were also concerned that, even within a chapter selected for the custom textbook, there was sometimes extraneous information that might prove distracting for students. Nevertheless, the online homework content associated with these textbooks was valuable, providing students with practice and rapid feedback.[40]

In addition, a freely accessible supporting Web site, authored in-house, presented information in an order similar to the classroom presentation of topics.[41] Some practice problems, with selected solutions, were also available at this site, and these aspects are currently being improved and expanded upon. During the spring 2015 semester, this online source became the sole textbook used for the course, although the online homework site was used via the same publisher as before.

ADVANTAGES OF AN INTEGRATED COURSE IN REACTIVITY

One goal of Reactivity I is to expose students to a variety of aspects of chemistry and biochemistry at a very early stage. Applications including diabetes, enzyme inhibitors as pharmaceuticals, polymers, and the synthesis of beneficial compounds all serve to catch students' imaginations. Different aspects seem to appeal to different students. Some students quickly identify themselves as fans of metals and inorganic chemistry, for example, whereas others favor the biochemical topics of the course. At the same time, this goal is accomplished without sacrificing a cohesive narrative that runs through the course.

Rather than presenting a series of unrelated topics, the course builds on common themes from one unit to the next. The use of curved arrows for electron flow, regardless of whether the subject is formally based in organic, inorganic, or biochemistry, is one tool that helps to tie the subject together. The design also presents the opportunity to develop an introductory-level understanding of thermodynamics and equilibrium across different contexts. In this treatment, students compare numerical values of ΔH or ΔS to judge whether reactions are likely to proceed, examine the balance between these factors using ΔG, and see how free energy translates into an equilibrium constant K. However, the use of nonstandard conditions and the relationship between free energy and reaction quotient are reserved for a later course, Chem 255. The same carbonyl chemistry that is a gateway into biochemical pathways is also an excellent platform for studying reversibility. In addition, coordination chemistry affords additional opportunities to illustrate ideas of enthalpy and entropy.

Another goal of the course design is to allow early entry into a range of biochemical processes, including enzyme catalysis and regulation. That goal appeals to a wide cross-section of students in introductory and foundation chemistry courses; this general approach has been described previously.[11,13]

The important place for inorganic chemistry in the course should not be overlooked. Following its widespread displacement from the traditional general chemistry course, the role of inorganic chemistry in the curriculum has been a subject of concern for inorganic chemists for many years[42] Reactivity I, together with subsequent reactivity courses, provides early exposure to some intriguing aspects of inorganic chemistry, including coordination compounds and organometallics. Thematically, this coverage fits within the parameters of a *Fundamentals and Selected Topics* treatment of inorganic chemistry.[43] Moreover, an understanding of metal−ligand

DOI: 10.1021/acs.jchemed.5b00103
J. Chem. Educ. 2015, 92, 2067−2073

binding and the resulting influence on ligand/substrate reactivity enhances students' understanding of enzyme catalysis.

Exposure to current research topics has been very appealing to some students. For example, a unit on coordination complexes begins with a review of Lewis acid−base interactions; an overview of common ligands; and a discussion of chelation, hapticity, and denticity. To understand some differential reactivity, students are introduced to Hard−Soft Acid Base Theory. At this point, students are exposed to an application of metal organic frameworks (MOFs), a field of vigorous current research.[44] This exercise helps students to consolidate key ideas about ligand binding and to see the utility of chemical structures to solve world problems such as hydrogen gas storage. Students are encouraged to read extra information about the importance of new materials; this use of current applications has generated early student interest in advanced topics.

■ ADDITIONAL CONSIDERATIONS

This first-year, second-semester course moves rapidly into organic reactions, so familiarity with line structures is assumed. Students have previously had practice with these structures in Chem 125, which includes some typically "organic" topics such as stereochemistry, conformational analysis, and structural trends in acidity and basicity. However, students have additional opportunities to practice with these structures at the beginning of Chem 250. Practice problems specifically related to the functional groups first encountered in the course are available, with solutions, in the online text. Additional, more general problems are available in the classroom workbook and in the online homework package.

This course invites comparisons with organic chemistry because of similar objectives in developing concepts of structure and reactivity. There are some unavoidable trade-offs if time is spent introducing aspects of inorganic and biochemistry at this level. An extensive discussion of structure determination via spectroscopic methods is not part of Chem 250 and it is introduced, instead, in lab-associated recitation sessions.

In addition, some level of sophistication is lost in the ability to assimilate organic reactions, especially in the context of multistep syntheses. Students do not spend as much time focused on the recognition of reagents and reaction products. An in-depth course on organic synthesis was introduced to help compensate for this loss.

Other aspects of organic chemistry have been moved to other portions of the reactivity sequence. Aliphatic nucleophilic substitutions, electrophilic additions to alkenes, and electrophilic aromatic substitutions are in Reactivity II, whereas radicals and pericyclic reactions are in Reactivity III (Table 1). Some facets of structural organic chemistry, including structural features of acids and bases, stereochemistry and conformation, were covered in Chem 125.[8]

Some aspects of inorganic and biochemistry are also sacrificed here. For example, in the context of coordination compounds, the inorganic chemistry that students can understand at this point is limited to cases that do not involve redox processes. Metal ions are presented as having static charges, rather than undergoing oxidations or reductions. However, within those limits, students can comprehend a range of reactions including the coordination and electrophilic activation of ligands, as well as migratory insertions, which involve no formal oxidation change at the metal. Reactivity II and III cover other topics from inorganic chemistry, including redox chemistry, but focus on additional aspects of coordination chemistry, organometallics, and bioinorganic chemistry. Opportunities to discuss inorganic descriptive chemistry are limited because of the constraint of the reactivity theme.

In biochemistry, some structural work was covered with biomolecules in Chem 125, particularly in the context of intermolecular forces and properties. Themes of biochemistry are revisited in a section on enzyme kinetics in Reactivity II. A number of systems are covered in some detail in Reactivity III, especially oxidative phosphorylation and photosynthesis. However, the diversity of carbohydrates are given little attention in this treatment and relatively little time is spent on the subject of nucleic acids.

In general, Chem 250 was developed as a foundation-level course in ACS-CPT parlance, i.e., it functions as a first introduction to a topic, and students may gain additional strengths by taking in-depth courses. Biochemistry majors, for example, take a subsequent course on biochemical pathways, and can gain insight into metabolic processes that builds on the exposure from Chem 125 and 250.

■ ASSESSMENT

The percentage of students receiving a grade of D, F, or W (% DFW) and the average student outcome (ASO), i.e., the mean grade earned by students on a 4.0 scale, can be useful indicators during curricular changes. In the case of Reactivity I, the reference point could be students in General Chemistry II, based on first-year status, or there is thematic similarity with Organic Chemistry I. The %DFW results from Reactivity I are mostly in line with Organic I (Table 3), but the numbers have improved as the course has matured. A dip in enrollment in Reactivity I during AY '12 probably reflects the introduction of off-sequence sections, so that students who might otherwise have taken the course in spring of 2012 could wait until the fall; these students are in the AY '13 data. More recently (starting AY '14), enrollment increased, again, because the course was added as a requirement for the nutrition major. Reactivity I also resembles Organic I for the ASO. Lower grades in a first year class raised concerns that students might be deterred from majoring in chemistry. On the contrary, the number of students declaring chemistry as a major has increased by over 60% since the new curriculum was introduced. In the period 1984−2014, an average of 15.2 (±5.5) majors graduated per year. Projected 2015−2017 graduates, assuming an attrition rate of 10% after declaration of a major in the second year, will average 24.6 (±1.7) per year. A similar rise has been seen in the numbers of biochemistry majors. Other factors behind this rise cannot be

Table 3. Average Student Outcome (ASO)[a] and Percent of Students with Grades of D, F, or W

	Students	ASO	%W	%DFW
Gen Chem II AY '05−'12[b]	212[c]	2.80	4.5	9.1
Org Chem I AY '05−'12	133[c]	2.66	6.0	10.0
Reactivity I AY '12	164	2.66	6.1	10.3
Reactivity I AY '13	200	2.68	7.5	11.0
Reactivity I AY '14	226	2.67	5.8	9.7
Reactivity I AY '15	243	2.51	3.3	8.2

[a]Mean grade earned in the class on a 4.0 scale. [b]AY # refers to end of academic year; i.e., AY '05 = academic year 2004−2005. [c]Average number per year during period reported.

DOI: 10.1021/acs.jchemed.5b00103
J. Chem. Educ. 2015, 92, 2067−2073

ruled out, but the substantial increase in majors suggests Chem 250 is not having an overall discouraging effect on students entering chemistry, despite the demands of the course.

To obtain an independent measure of student performance in Reactivity I, selected questions from different ACS exams (inorganic, organic, biochemistry, and GOB) were chosen. In AY '12, 34 ACS exam questions (selected from different forms) were included in an online final exam administered by ACS. Sixteen more ACS questions were added in AY '13, but two others were removed because of content that was moved to another course. Three more questions were added in AY '14; this final group of 51 questions was again presented in AY '15. Because suitable ACS questions were not found for some concepts, 20 other questions were written in-house. The latter group of questions remained the same each year, but results are not reported here because of the lack of an external standard. The difficulty index, or fraction of students choosing the correct answer for each question, was compared to national norms published for each of the corresponding ACS exams questions (Table 4). A description of results from statistical analysis of individual questions is provided in the Supporting Information. In general, the results appear to be comparable to the national data. The results compare the performance of first-year students in Chem 250 with their peers having between one and three years additional experience. A comparison with baseline data, pre-Chem 250, is complicated for similar reasons. Over the 10-year period prior to introduction of the course, students performed very well on standard ACS exams in inorganic (average score, 63%; nationally normed average score, 55%) and organic chemistry (average score, 70%; nationally normed average score, 56%). The ACS biochemistry exam was not previously used. It is not clear whether the difference stems from the different curriculum or the different maturity levels of students in the two groups.

Table 4. Comparison of Average Difficulty Index on ACS Exam Questions in Reactivity I to Nationally Reported Data[a]

	Average difficulty index	
Year (no. questions)	Chem 250	National[b]
AY '12 (34)	0.51	0.54
AY '13 (48)	0.54	0.56
AY '14 (51)	0.58	0.57
AY '15 (51)	0.56	0.57

[a]The difficulty index is the fraction of students with the correct answer to a question. [b]The average of the difficulty indices of all questions used, based on national norms.

In the past, students have taken the Major Field Achievement Test (MFAT). Average percentile scores, both overall and in individual subsections such as organic or inorganic chemistry, have typically ranged between 71st and 85th percentile. The data from graduating seniors in AY '15, the first group who took the entire new curriculum, appear to be in the same range, but it is unwise to draw conclusions from one year of data. Details are provided in the Supporting Information.

CONCLUSIONS

An integrated course on reactivity in organic, inorganic, and biochemistry was described. In the past few years, there has been interest in developing new approaches to the chemistry curriculum. This report offers one more variation to consider. Strengths of this approach include an early exposure to organic, inorganic, and biochemistry, as well as reinforcement of areas where these three fields overlap, such as enzyme catalysis, organometallics, and bioinorganic chemistry. On standard exam questions, students performed comparably to their peers at higher levels at other institutions. By final year, student performance on exams was comparable to that of previous students taking a traditional curriculum.

This curriculum demonstrates that chemistry can be delivered with a more integrated theme without sacrificing student performance when judged by traditional parameters. We are currently implementing other courses for this new curriculum and will continue to report on developments in the future. It is hoped that this report encourages other instructors to adopt innovative models of their own.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00103.

Sample pages from Reactivity I workbook, with accompanying notes from the daily schedule for the class; information on accessing electronic or hard copies of the workbook (PDF)

AUTHOR INFORMATION

Corresponding Author

*E-mail: cschaller@csbsju.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 1043566. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors wish to acknowledge contributions and feedback provided by Henry Jakubowski and Alicia Peterson.

REFERENCES

(1) Elving, P. J. The Curriculum in Chemistry. *J. Chem. Educ.* **1952**, *29* (5), 216–217.

(2) (a) Larive, C. K.; Polik, W. F. New ACS Guidelines Approved by CPT. *J. Chem. Educ.* **2008**, *85* (4), 484–487. (b) McCoy, A. B.; Darbeau, R. W. Revision of the ACS Guidelines for Bachelor's Degree Programs. *J. Chem. Educ.* **2013**, *90* (4), 398–400.

(3) Whitesides, G. M.; Deutch, J. Let's Get Practical. *Nature* **2011**, *469* (7328), 21–22.

(4) Shulman, J. Chemistry in the Premedical Curriculum: Considering the Options. Revisiting the Premed Curriculum. *J. Chem. Educ.* **2013**, *90* (7), 813–815.

(5) Carroll, M. K. Moving from Recommendations to Innovations: Increasing the Relevancy and Effectiveness of Chemistry Education. *J. Chem. Educ.* **2013**, *90* (7), 816–819.

(6) Cooper, M. M. The New MCAT: An Incentive for Reform or a Lost Opportunity? *J. Chem. Educ.* **2013**, *90* (7), 820–822.

(7) Schaller, C. P.; Graham, K. J.; Johnson, B. J.; Fazal, M. A.; Jones, T. N.; McIntee, E. J.; Jakubowski, H. V. Developing and Implementing a Reorganized Undergraduate Chemistry Curriculum Based on the Foundational Chemistry Topics of Structure, Reactivity, and Quantitation. *J. Chem. Educ.* **2014**, *91* (3), 321–328.

DOI: 10.1021/acs.jchemed.5b00103
J. Chem. Educ. 2015, 92, 2067–2073

(8) Schaller, C. P.; Graham, K. J.; Johnson, B. J.; Jakubowski, H. V.; McKenna, A. G.; McIntee, E. J.; Jones, T. N.; Fazal, M. A.; Peterson, A. A. Chemical Structure and Properties: A Modified Atoms-First, One-Semester Introductory Chemistry Course. *J. Chem. Educ.* **2015**, *92* (2), 237−246.
(9) Goedhart, M. J. A New Perspective on the Structure of Chemistry as a Basis for the Undergraduate Curriculum. *J. Chem. Educ.* **2007**, *84* (6), 971−976.
(10) Clark, R. W. The Structure of Chemistry. *J. Chem. Educ.* **1999**, *76* (12), 1612−1613.
(11) Malinak, S. M.; Logan Bayline, J.; Brletic, P. A.; Harris, M. F.; Iuliucci, R. J.; Leonard, M. S.; Matsuno, N.; Pallack, L. A.; Stringfield, T. W.; Polvani Sutherland, D. P. The Impacts of an "Organic First" Chemistry Curriculum at a Liberal Arts College. *J. Chem. Educ.* **2014**, *91* (7), 994−1000.
(12) (a) Ege, S. N.; Coppola, B. P.; Lawton, R. G. The University of Michigan Undergraduate Chemistry Curriculum 1. Philosophy, Curriculum, and the Nature of Change. *J. Chem. Educ.* **1997**, *74* (1), 74−83. (b) Coppola, B. P.; Ege, S. N.; Lawton, R. G. The University of Michigan Undergraduate Chemistry Curriculum 2. Instructional Strategies and Assessment. *J. Chem. Educ.* **1997**, *74* (1), 84−94.
(13) Reingold, I. D. Bioorganic First: A New Model for the College Chemistry Curriculum. *J. Chem. Educ.* **2001**, *78* (7), 869−871.
(14) McMinn, D. G.; Nakamaye, K. L.; Smieja, J. A. Enhancing Undergraduate Education: Curriculum Modification and Instrumentation. *J. Chem. Educ.* **1994**, *71* (9), 755−758.
(15) Garkov, V. Problems of the General Chemistry Course and Possible Solutions: The 1−2-1 General/Organic/General Curriculum and its Challenges. *Khimiya* **2006**, *15* (2), 86−100.
(16) Rettich, T. R.; Bailey, D. N.; Frank, F. J.; Frick, J. A. An Integrated Curriculum for First- and Second-Year Courses. *J. Chem. Educ.* **1996**, *73* (7), 638.
(17) Cartrette, D. P.; Miller, M. L. Blending Organic and General Chemistry: A Unified and Holistic Curriculum Reform Effort. In *Advances in Teaching Organic Chemistry*; Pacheco, K. A. O., Duffy-Matzner, J. L., Eds.; ACS Symposium Series 1108; American Chemical Society: Washington, DC, 2012; pp 151−175.
(18) Reingold, I. D. Inverting Organic and Biochemistry: A Curriculum Tweak that Benefits All. *J. Chem. Educ.* **2004**, *81* (4), 470−474.
(19) Duffy-Matzner, J. L.; Mays, J. R. Revamping a Second Semester Organic Chemistry Course To Meet the New ACS Biochemistry Requirements. In *Advances in Teaching Organic Chemistry*; Pacheco, K. A. O., Duffy-Matzner, J. L., Eds.; ACS Symposium Series 1108; American Chemical Society: Washington, DC, 2012; pp 177−183.
(20) Goess, B. C. Development and Implementation of a Two-Semester Introductory Organic-Bioorganic Chemistry Sequence: Conclusions from the First Six Years. *J. Chem. Educ.* **2014**, *91* (8), 1169−1173.
(21) Bretz, S. L.; Fay, M.; Bruck, L. B.; Towns, M. H. What Faculty Interviews Reveal About Meaningful Learning in the Undergraduate Chemistry Laboratory. *J. Chem. Educ.* **2013**, *90* (3), 281−288.
(22) Bowman, B. G.; Karty, J. M.; Gooch, G. Teaching a Modified Hendrickson, Cram, and Hammond Curriculum in Organic Chemistry. *J. Chem. Educ.* **2007**, *84* (7), 1209−1216.
(23) Houseknecht, J. B. Topic Sequence and Variability of Selected Organic Chemistry Textbooks. *J. Chem. Educ.* **2010**, *87* (6), 592−597.
(24) Long, K. M. Revised First-Year Curriculum with an Inorganic Chemistry Course. *J. Chem. Educ.* **2003**, *80* (10), 1172−1173.
(25) Miessler, G. L.; Spessard, G. O. Organometallic Chemistry: A Course Designed for Sophomore Chemistry Students. *J. Chem. Educ.* **1991**, *68* (1), 16−18.
(26) Berg, S.; Ghosh, A. Arrow Pushing: A Rational, Participatory Approach to Teaching Inorganic Chemistry. *J. Chem. Educ.* **2011**, *88* (12), 1663−1666.
(27) Ochiai, E.-I. Free Radicals and Metals in Biology: Principles and Applications in Bioinorganic Chemistry VI. *J. Chem. Educ.* **1993**, *70* (2), 128−133.
(28) Prilliman, S. G. Integrating Particulate Representations into AP Chemistry and Introductory Chemistry Courses. *J. Chem. Educ.* **2014**, *91* (9), 1291−1298.
(29) Bretz, S. L.; Fay, M.; Bruck, L. B.; Towns, M. H. Novak's Theory of Education: Human Constructivism and Meaningful Learning. *J. Chem. Educ.* **2001**, *78* (8), 1107−1116.
(30) Cardellini, L. Conceiving of Concept Maps to Foster Meaningful Learning: An Interview with Joseph D. Novak. *J. Chem. Educ.* **2004**, *81* (9), 1303−1308.
(31) Schaller, C. P.; Graham, K. J.; Johnson, B. J. Modules for Introducing Organometallic Reactions: A Bridge between Organic and Inorganic Chemistry. *J. Chem. Educ.* **2015**, *92* (6), 986−992.
(32) Wijtmans, M.; van Rens, L.; van Muijlwijk-Koezen, J. E. Activating Students' Interest and Participation in Lectures and Practical Courses Using Their Electronic Devices. *J. Chem. Educ.* **2014**, *91* (11), 1830−1837.
(33) Parker, L. L.; Loudon, G. M. Case Study Using Online Homework in Undergraduate Organic Chemistry: Results and Student Attitudes. *J. Chem. Educ.* **2013**, *90* (1), 37−44.
(34) McKenna, A. G.; Johnson, B. J.; McIntee, E. J.; Peterson, P. A. Use of Pre-Class Assignments to Encourage Student Participation. *Abstracts of Papers, 243rd ACS National Meeting & Exposition*, San Diego, CA, March 25−29, 2012; CHED-1618.
(35) Woods, D. R. Problem-Oriented Learning, Problem-Based Learning, Problem-Based Synthesis, Process Oriented Guided Inquiry Learning, Peer-Led Team Learning, Model-Eliciting Activities, and Project-Based Learning: What is Best for You? *Ind. Eng. Chem. Res.* **2014**, *53* (13), 5337−5354.
(36) Gorzynski Smith, J. *Organic Chemistry*, 3rd ed.; McGraw-Hill: New York, 2011.
(37) Rodgers, G. E. *Descriptive Inorganic, Coordination, and Solid State Chemistry*, 3rd ed.; McGraw-Hill: New York, 2012.
(38) Campbell, M. K.; Farrell, S. O. *Biochemistry*, 7th ed.; McGraw-Hill: New York, 2012.
(39) McMurry, J. E. *Organic Chemistry*, 8th ed.; McGraw-Hill: New York, 2012.
(40) OWL, Version 2, Cengage Learning. http://www.cengage.com/owlv2 (accessed Dec 2014).
(41) Schaller, C. P. *Structure and Reactivity in Organic, Biological and Inorganic Chemistry*. http://employees.csbsju.edu/cschaller/ROBI1.htm (accessed Dec 2014).
(42) Verkade, J. G. Inorganic Chemistry and the New CPT Flexible Curricula. *J. Chem. Educ.* **1991**, *68* (11), 911−914.
(43) Raker, J. R.; Reisner, B. A.; Smith, S. R.; Stewart, J. L.; Crane, J. L.; Pesterfield, L.; Sobel, S. G. Foundation Coursework in Undergraduate Inorganic Chemistry: Results from a National Survey of Inorganic Chemistry Faculty. *J. Chem. Educ.* **2015**, *92* (3), 973−979.
(44) Furukawa, H.; Cordova, K. E.; O'Keeffe, M.; Yaghi, O. M. The Chemistry and Applications of Metal-Organic Frameworks. *Science* **2013**, *341* (6149), 1230444.

DOI: 10.1021/acs.jchemed.5b00103
J. Chem. Educ. 2015, 92, 2067−2073