JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

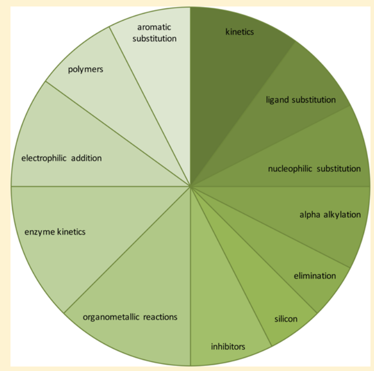
Reactivity II: A Second Foundation-Level Course in Integrated Organic, Inorganic, and Biochemistry

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

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 described that integrates material related to reactivity in organic, inorganic, and biochemistry. Designed for second-year students, the course serves majors in chemistry, biochemistry, and biology, as well as prehealth-professions students. Building on an earlier course that developed concepts of nucleophiles and electrophiles in organic carbonyl chemistry and coordination compounds, Reactivity II explores the concept of mechanistic alternatives in substitution reactions of alkyl halides and transition metal complexes. Kinetics is introduced as a diagnostic tool for understanding mechanisms, and is extended to the study of enzyme-catalyzed reactions. An introduction to the reactivity of alkenes and aromatics rounds out students' understanding of reactions involving electrophiles and nucleophiles.



KEYWORDS: *Second-Year Undergraduate, Organic Chemistry, Inorganic Chemistry, Biochemistry, Catalysis, Kinetics, Reactions, Analogies/Transfer, Enzymes, Organometallics*

■ INTRODUCTION

Interest in innovative approaches to the structure of chemistry programs has been inspired by the revision of guidelines from the American Chemical Society Committee on Professional Training (ACS-CPT).[1] 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 build on their knowledge, either in more advanced treatments of the foundation domains or in special topics courses.

Rather than isolating instruction into these separate domains, an alternative organization of the chemistry curriculum has been proposed based on courses in three general areas: structure, reactivity, and quantitation.[2] Structure includes a range of considerations such as periodic trends, unit cells in extended solids, stereochemistry, and conformation.[3] Reactivity includes the prediction of reactions and understanding of mechanisms across organic, inorganic, and biochemistry.[4] Quantitation encompasses the usual mathematical considerations of chemistry, prominent in both physical and analytical chemistry, but also is important elsewhere. This organizational structure has been developed as the basis for a revised chemistry curriculum (see Table 1) at the College of Saint Benedict/Saint John's University (CSB/SJU).

Interdisciplinary science education allows students to develop a more coherent view of the world; consequently, it is considered a priority even at primary and secondary levels.[5] At the undergraduate and graduate levels, authors have noted the vast potential for solving problems that lies at the interface of traditional fields of study.[6] However, a recent report from the National Science Foundation suggests that significant barriers to interdisciplinary work remain embedded in the structures of academia, and innovative approaches are needed that will make students and researchers accustomed to working across boundaries.[7]

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

Course (Semester)	Emphasis
Chem 125: Structure and Properties (first)[a]	Atoms, solids, molecules, geometry, stereochemistry, intermolecular attraction, acid−base
Chem 250: Reactivity I (second)	Basic equilibrium, carbonyl chemistry, coordination compounds, metabolic pathways
Chem 251: Reactivity II (third)	Kinetics, enzyme inhibition, aliphatic substitution, alkene addition, arene substitution, organometallics
Chem 255: Macro Chem Analysis (fourth or fifth)[b]	Quantitative thermodynamics, equilibria, electrochemistry, statistics
Chem 315: Reactivity III (fourth or fifth)[b]	Redox, radicals, oxidative phosphorylation, photochemistry, photosynthesis, pericyclics
Chem 318: Micro Chem Analysis (fifth or sixth)	Quantum chemistry, spectroscopy

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

Received: February 12, 2016
Revised: May 20, 2016
Published: June 2, 2016

There is a growing body of literature on interdisciplinary approaches to chemistry; numerous examples can be found in this journal. Apart from the need for interdisciplinary research, the relevance of bridging disciplines with chemistry has been cited as a high priority by industrial chemists.[8] Interdisciplinary training has been applied both in the laboratory and in lecture courses and from the high school level to the advanced undergraduate level. Connections between different domains within chemistry have received less attention, and so a curriculum for majors as outlined in Table 1 remains outside the norm.

Other suggestions have been put forward for the reorganization of the chemistry curriculum, although along different lines.[9,10] These authors have commented on the seemingly arbitrary distinctions between organic, inorganic, and biochemistry, for example, in the face of myriad strains of the field driven by new research in areas as diverse as materials, food chemistry, and forensics. In response, one author has called for the complete despecialization of undergraduate courses (just basic, intermediate, or advanced chemistry rather than organic, physical, or analytical chemistry).[10] Another author has suggested reorganizing courses to reflect tasks of a working chemist (such as synthesis, analysis, or theory development).[9] These models may seem radical, but they may also serve to inspire new activities even in conventional chemistry courses. Because curricular change requires a great time investment, it might be easier to approach change incrementally by reframing questions asked within traditional courses so that they underscore central questions of chemistry or that highlight current priorities of the scientific community and society.[11] Consequently, there is potential benefit to the chemistry community in sharing novel constructions of the chemistry curriculum, either because other instructors wish to adopt a similar approach or because associated ideas can be applied in other contexts. These contexts could range from a quiz question or classroom exercise all the way to a full-scale curricular redesign.

Structure, Reactivity, and Quantitation

The fundamental importance of structure in chemistry is illustrated by a number of key topics, including the nature of atoms, molecules and ions; conceptual models of bonding; and the three-dimensional shape found in both molecules and crystalline structures. Gillespie has enumerated these considerations among "the great ideas" of chemistry.[12] Structure–property relationships, and especially intermolecular attractions, also hold a prominent place in explaining both chemical and biochemical phenomena; these ideas have pride of place in an analogous list from Atkins.[13] Other topics build naturally on these concepts, and so they have traditionally been taught in a general chemistry course for first-year college students. However, some important elements of structure, such as stereochemistry and conformational analysis (the three-dimensional shape of molecules), are not usually included in general chemistry. At CSB/SJU, structure is the basis for an introductory, prefoundation course in chemistry, called Structure and Properties (Chem 125).[3] That course follows a progression of topics from atomic structure through ions to molecules, and it includes an emphasis on molecular shape and the relationship between the structure of molecules and their properties.

A mathematical approach to chemistry is given light treatment in the introductory course in structure (Chem 125). Students are first exposed to topics in a qualitative sense to see the big picture and how things fit together. This approach often excites students' interest, motivating them to delve deeper into chemistry through mathematical equations. This aspect of chemistry, however, is reserved for later courses on quantitation. In Macroscopic Chemical Analysis and Microscopic Chemical Analysis (Chem 255 and Chem 318), concepts of physical chemistry are developed and then applied to problems in analytical chemistry. This combination is not novel; traditional general chemistry was conceived as a course in integrated physical and analytical chemistry.[14] However, both Macroscopic Chemical Analysis and Microscopic Chemical Analysis provide a more advanced examination of thermodynamics and quantum mechanics, respectively. Although there may be some concern that students are unprepared for these topics without a rigorously mathematically oriented preparation in general chemistry, the correlation between completion of general chemistry and subsequent performance in physical chemistry has already been questioned.[15] Additional maturity in students may compensate for the lack of early exposure to these topics. At CSB/SJU, students also gain additional background in reactivity before proceeding to Macroscopic Chemical Analysis and Microscopic Chemical Analysis. As seen in Table 1, students typically take these quantitative courses in their fourth, fifth, or sixth semester.

Reactivity is "perhaps the most important" of chemistry's basic ideas; it is indeed "the heart of chemistry", according to Gillespie.[12] To understand reactions is a central concern of chemists, and the ability to carry reactions out is crucial to the economy. Ideally, courses in reactivity would illustrate similar principles across organic, inorganic, and biochemistry; the need to reinforce commonalities across these domains has been discussed for some time.[16] However, we have long been conditioned to think that these topics belong together only in a course designed for nursing majors, not for scientists. That attitude has changed as instructors have seen the value of engaging biology majors and prehealth students at an earlier stage of their education in chemistry; several authors have discussed ways to draw these students into the conversation.[17−19] As a result, the study of organic chemistry has been coupled to the storyline of biochemistry or bioorganic chemistry, as seen in some more recent textbooks.[20,21] In contrast, the connections between organic and inorganic chemistry that are so obvious in present-day research and practice remain relatively untouched in the classroom, although some organic textbooks now include some transition metal chemistry.[22,23] At CSB/SJU, a three-course lecture sequence (Chem 250, Chem 251, and Chem 315) is entirely devoted to the development of principles of reactivity in organic, inorganic, and biochemistry.

Herein is described the second course (Chem 251: Reactivity II) in that sequence of courses. This lecture course has been taught since fall 2013. Descriptions of the prerequisite course in structure, Chem 125 (Structure and Properties) and the first reactivity course, Chem 250 (Reactivity I), have been reported already.[3,4] Details on a series of separate laboratory courses will be communicated at a later date.

DOI: 10.1021/acs.jchemed.6b00116
J. Chem. Educ. 2016, 93, 1383−1390

CHEM 251: REACTIVITY II

Context for the Course: Prerequisite and Theoretical Framework

The immediate prerequisite for Chem 251 is Chem 250.[4] In Chem 250, the groundwork for an understanding of biochemical pathways is laid through an extensive look at the organic chemistry of carbonyl compounds, similar to the approach espoused by Reingold.[17] This emphasis is important for the plurality of biology and prehealth majors enrolled in the course. At the same time, a focus on carbonyl chemistry allows for the development of basic ideas about enthalpy and entropy changes in reactions, as well as control of equilibrium through Le Chatelier's Principle. Concepts of inorganic chemistry are also introduced in the context of coordination chemistry, including a discussion of ligand field theory; examples of activities used in class have been described already.[24] The inclusion of coordination chemistry brings additional examples of enthalpy and entropy changes and also facilitates discussion of the role of Lewis acids in biochemical reactions. In addition, close parallels are found between organic carbonyl chemistry and the reactivity of transition metal carbonyls in organometallics; a description of this coverage has been reported previously.[25]

As in the case of its prerequisite, Chem 251: Reactivity II was designed so that new ideas would build on familiar concepts as much as possible. A precedent for this approach can be found in Novak's theory of meaningful learning.[26] Efforts were also made to convey stories about chemical processes that are relevant to everyday life, allowing students to place ideas in a significant and easily recalled context. The return of topics at later dates and in new contexts also provides an opportunity for "integrative reconciliation" in which previous errors in thinking can be recognized and corrected.[27]

Overview of Course Content

The topics covered in Chem 251 are outlined in Table 2. The course continues to address some of the standard topics of organic reactivity not seen already in Chem 250. These new topics include aliphatic nucleophilic substitution and elimination, electrophilic addition to alkenes, and electrophilic aromatic substitution. Aliphatic nucleophilic substitution and elimination are usually covered in a first-semester course in organic chemistry, but the multiple mechanistic pathways available for these reactions can be perplexing for students, as illustrated by a number of tools developed to help keep things straight.[28] For that reason, these ideas are introduced during the students' second course involving reactions of organic chemistry, when students are more prepared for this subtlety.

Table 2. Order of Topics in Chem 251: Reactivity II

Topic	Class Periods[a]
Introduction to kinetics	3
Ligand substitution mechanisms	3
Nucleophilic substitution and elimination	3
Competing reactions	2
Nucleophilic substitutions in synthesis	3
Alpha alkylations	3
Nucleophilic substitution at silicon	2
Drug design and enzyme inhibition	3
Oxidative addition and reductive elimination	2
Organometallics in catalysis	3
Michaelis−Menten and Lineweaver−Burke	3
Enzyme kinetics applications	2
Electrophilic addition to alkenes	4
Electrophilic aromatic substitution	3
Alkenes in polymer chemistry	2
Eyring plots: application in polymers	1

[a]In 55 min periods: 42 total, with tests and quizzes included during this time.

Mechanisms of ligand substitution in coordination complexes are also covered in Chem 251, for several reasons. These reactions make interesting comparisons to the S_N1 and S_N2 pathways from organic chemistry; a brief discussion of mechanisms has been published in this journal.[29] Similar choices must be made in evaluating what pathway will be taken to replace one ligand with another, although the contributing factors are different. Both classes of reactions also present an opportunity to study kinetics within a real context, rather than reducing it to the symbolic abstraction of molecule A reacting with molecule B to form molecule C.

This thread is strong enough that kinetics becomes a secondary theme for the course. Although this subject is used as a way to practice mathematical reasoning and graphical analysis, a greater emphasis is placed on developing some underlying concepts before engaging in drill problems on the determination of rate laws. These ideas include the need for molecular collisions, available energy versus the energy needed to surmount an activation barrier, the role of catalysts, and the change in reaction rate over time; a previous author reported using this approach to build a conceptual understanding of the topic.[30] In addition to using kinetics as a diagnostic tool to distinguish between associative and dissociative substitution mechanisms, the idea of kinetic vs thermodynamic control over competing pathways is examined in the context of alpha-alkylations.

The subject of biochemical kinetics is also discussed in Chem 251. The concept of saturation is introduced using a simple enzyme−substrate complex model. The same model is easily extended to introduce the idea of competitive inhibitors and modified to include the variation of noncompetitive and uncompetitive inhibitors; a number of activities have been reported to help students grasp the differences.[31] With some conceptual models in place, students examine the mathematical approach to biochemical kinetics, including the analysis of limiting cases in the Michaelis−Menten equation in order to gain insight into the parameters K_m and k_{cat}. Students also work with the graphically more accessible Lineweaver−Burke equation.

The parallel between catalysis facilitated by enzymes and by transition metal complexes is used as an opportunity to look at organometallic chemistry.[27] Students learn to work through catalytic cycles for a variety of industrially important processes. Oxidative additions are introduced by analogy to nucleophilic substitution, one of the mechanistic pathways available for this reaction, and reductive elimination is seen as the microscopic reverse in an equilibrium situation. Having already learned how to count electrons in coordination complexes using the oxidation state method, students readily grasp the redox change here, even though they have not extensively studied redox processes, stoichiometry, and balancing redox reactions at the college level because single-electron chemistry is described in Chem 315 (Reactivity III). Insertion into alkenes is also reinforced in Chem 251 by the corresponding electrophilic additions of organic chemistry.

DOI: 10.1021/acs.jchemed.6b00116
J. Chem. Educ. 2016, 93, 1383−1390

CHEM 251: EXAMPLES OF TOPICAL COVERAGE

Substitution Reactions

Coverage of substitution reactions takes up almost 40% of Chem 251 (17 of 42 class periods). Although this treatment is too extensive to describe in detail in a paragraph, a brief look will highlight how reactions from different areas of chemistry may be used to reinforce common themes of reactivity. These reactions are introduced in Chem 251 through ligand substitutions in coordination complexes, rather than aliphatic nucleophilic substitutions, which are complicated by competing elimination reactions. The discussion of ligand substitution is further limited to purely associative and dissociative mechanisms in order to provide a simpler introduction to the topic. Four class periods are devoted to ligand substitution, including brief introductions to some related topics: the spectrochemical series, Jahn−Teller distortions, and the trans effect.[26,27] Emphasis is placed on the use of rate laws to experimentally distinguish these two reaction pathways, as well as factors that influence the mechanism. Another four days are spent introducing aliphatic nucleophilic substitution, in close analogy to ligand substitution, as well as 1,2-elimination. This discussion again includes a treatment of rate laws, much like the treatment in an organic chemistry course. The factors that govern the competition between these four reactions (S_N1, S_N2, E1, E2) are summarized on a fifth day. Six subsequent days are spent exploring the use of these (mostly S_N2) reactions in organic synthesis. Finally, the formation and cleavage of silyl ethers, a mechanism the students have not previously encountered, is used as an opportunity to revisit examples of rate laws in mechanistic determination for a third time.[32]

Drug Design

Introduction to drug design is a topic that brings together material from previous courses (Chem 125: Structure and Properties; Chem 250: Reactivity I) to help provide context for an idea from Chem 251 (see Supporting Information, sections SI3 and SI4). This section of the course follows a unit on the use of aliphatic nucleophilic substitution in synthesis. Two full class periods are devoted to drug design. Before coming to class, students are also guided through a brief review of enzyme strategies, introduced in Chem 250. In the classroom, qualitative models are introduced to describe different modes of inhibition, and the consequence of each model for rate of catalysis is presented graphically using both Michaelis−Menten and Lineweaver−Burke plots. However, the mathematical expressions for these relationships are introduced about 2 weeks later, after students have already worked repeatedly with these graphs, so that students can experience the "eureka" moment of discovering *why* the y-intercept was related to k_{cat}, or why the x intercept was related to K_m. On the second day in the classroom, the drug design section continues with a number of short case studies that illustrate topics from Chem 125 (intermolecular forces), Chem 250 (enzyme strategies, coordination compounds), and Chem 251 (enzyme inhibition and kinetics, synthesis of drug targets). Application-oriented topics like this one do not take up very much class time but are indispensable in generating student interest in science; it has been reported that building "connected knowledge" in this way is especially important for women.[33]

Catalytic Cycles

The study of organometallic catalytic cycles is another example of a topic that illustrates this integrated approach to chemistry. This topic draws together concepts mostly from organic and inorganic chemistry, as we have described previously.[27] It is becoming more common to include this topic in a second-year course in organic chemistry. However, its inclusion in Chem 251, together with the closely allied study of enzymes and enzyme kinetics, allows for a deeper discussion of general considerations of catalysis. Key steps of binding, transformation, and product release are common to both biochemical and industrial catalysis, as is the related idea of turnover. Placing these topics closely together allows for increased repetition of these themes in different contexts.

IMPLEMENTATION DETAILS

Classroom Organization

Instruction in Chem 251 takes place in a very interactive classroom environment; flipped classrooms and related approaches continue to garner interest among chemistry instructors.[34,35] In fact, there are a range of active learning approaches for classroom instruction in the sciences.[36] Most of the classroom details described here were already practiced in general chemistry and organic chemistry at CSB/SJU and thus are not truly part of the curricular revision; they are included in order to paint a complete picture of how the curriculum is implemented on a day-to-day basis. Furthermore, several sections of Chem 251 are taught each semester by different instructors, and there is not one rigorously prescribed course script. Although a standard daily schedule of topics is agreed on, and rough point totals in different categories are adhered to, individual instructors are allowed some room to try different things. Nevertheless, it is possible to provide a general description of what all students in the course would experience.

In Chem 251, students prepare for class by reading assigned materials from an in-house online textbook or from Chemwiki.[37,38] The reading is not usually enforced, but most students who have clearly done the readings beforehand tend to perform better. Occasional "passports" (5−10 per semester) require students to fill out a one or two page worksheet; these assignments usually review a previous topic that will be built on in class or else require a rote exercise that lays the groundwork for a classroom discussion.

The class period typically starts with a short (<10 min) lecture, with shorter (∼5 min) recaps at the middle and end of the period. Students spend the remainder of the period (∼35 min) in small groups solving problems in a workbook (see Supporting Information, section SI4). Classrooms are furnished with round tables to facilitate teamwork.

Between classes, students might be assigned homework problems, either on paper (often once per week) or online (via OWL or other platforms, two or three times per week).[39] Chem 251 is a four-credit class that meets for just under 3 h per week; thus, students are expected to spend about 11 hours per week, or 1.5 h per day, preparing for class, reviewing, and completing assignments.

Quizzes or tests, varying in length, are held during class time about once per week. Allowance for these tests obviously changes the class schedule for that day; most instructors allow about 15 min for a regular quiz, with occasional longer tests (perhaps once per month) taking 30 min. Some instructors revise the schedule to allow two or three tests that take an entire class period; that accommodation involves cutting down on practice or application problems during class time, often by converting these pieces into homework sets, or leaving out

DOI: 10.1021/acs.jchemed.6b00116
J. Chem. Educ. 2016, 93, 1383−1390

another classroom activity rather than skipping core material. In addition, students usually complete a brief quiz at the beginning of class (five multiple choice questions via Socrative, but clickers and other tools could be used).[40] The Socrative is opened while students are waiting for class to begin, and most students have finished by the start of the class period.

A total of 42 class periods in a semester is the norm for Monday−Wednesday−Friday classes at CSB/SJU and a few other colleges in the Upper Midwest. More commonly, the typical semester allows about 39 class periods for M−W−F classes, and sometimes fewer. Other departments opting for wholesale adoption of this new curriculum would have to make decisions about coverage. It is possible that a few special topics could be skipped, such as nucleophilic substitution at silicon, the trans effect, or diffusion across membranes, leaving those topics for in-depth courses. These choices should not be interpreted as recommendations but are simply a representative set from organic, inorganic and biochemistry; others could also be suggested. Alternatively, time could be saved by skipping some hands-on exercises, such as a biochemical kinetics activity with nuts and bolts.[31]

Instructional Resources

There are workbooks available commercially to support traditional chemistry classes, but the integrated approach in Chem 251 necessitated the production of a new workbook addressing the topics described above. Initially put together using old classroom handouts, quiz questions, and a workbook previously developed for use in organic chemistry classes, this resource was revised annually for the first few years that the course was offered. The current workbook is approximately 450 pages long and includes sections that develop the basic concepts of each topic based on previous knowledge. Subsequent sections pose problems that allow students to apply their knowledge to new scenarios.

With the growing volume of online texts and course notes available, Chem 251 readings could easily be selected from existing resources such as ChemWiki.[39] The course-specific online text, Structure and Reactivity in Organic, Biological, and Inorganic Chemistry, was developed gradually over the last dozen years.[38] It was initially planned as a resource with review materials for students in organic chemistry. Additional readings have been written in other areas, especially inorganic chemistry. Hundreds of practice problems, many with solutions, are also available at this site. The site is periodically improved and expanded upon.

Shepherding Curricular Changes

Implementing a radical update to the curriculum requires department-wide coordination, support from administrators, and communication with other departments. The process may require a significant amount of time, both in terms of the need to prepare course materials and to permit adequate consensus-building among participants. The possibility of curricular revision at CSB/SJU was first seriously discussed at a departmental workshop in August, 2009; the first cohort of majors graduated from the curriculum six years later. However, many of the elements of the curriculum sprang from much earlier discussions among small groups of faculty as well as innovations in traditional courses, both dating from the 1990s.

During the two years between that initial meeting and the beginning of the rollout of new courses, which were phased in one semester at a time, a significant amount of work had to be done within the department. At the outset, it was not at all clear what the new curriculum would look like. Small groups were formed to develop models for various aspects of the project and report back to the department for feedback. Department meetings were devoted to refining proposals and building consensus. A grant proposal was submitted to the National Science Foundation (NSF) to fund work on the project.

Tremendous effort was devoted to developing new instructional materials. A department member was assigned to redevelop an existing online general chemistry review for organic chemistry students into a text for the Structure and Reactivity portions of the new curriculum. Another instructor revised existing, in-house organic chemistry workbooks, in use since about 2004, to be used in the Reactivity sequence, a task that required the development of significant amounts of new material. However, the magnitude of the workbook revision was buffered by the amount of innovation that had already been done within the traditional organic chemistry course at CSB/SJU. An early (September or October) introduction to spectroscopy had been implemented in the late 1990s; this approach has also been used by instructors at other institutions.[26] A first-semester treatment of carbonyl chemistry had been introduced around 2000, similar to an approach used by others.[25] Modules on organometallic reactions had also been tried on campus in the early 2000s. In addition, other faculty members were asked for contributions to both the online and workbook endeavors, usually in the form of old classroom worksheets or old test questions for use as practice problems.

Coordination with other departments is always important for chemistry. For the education department, that meant filling out an extensive survey identifying how and where a series of learning goals and objectives were met within the new curriculum. Clear communication with the biology department was accomplished through a formal presentation, delivered by a small group of chemists to a biology department meeting, followed by a discussion. Informal communication between biology and chemistry, including chair-to-chair communication, had earlier proven insufficient when it became apparent that not all members of either department ever seemed to get the entirety of what the other department wished to say. Discussion between the two departments was further complicated by the fact that chemistry is located on the College of Saint Benedict campus, whereas biology is housed seven miles west at Saint John's University. Additional feedback was sought by the chemistry department from admissions officers at the medical schools most frequently attended by our graduates; this feedback took the form of a survey.

The administration agreed to hire two additional adjunct instructors for a two-year period while the new curriculum was being introduced; this situation is not unusual in the department given that one or two faculty members are often on sabbatical. This provision allowed for the old curriculum to be offered for a discrete period while new courses were introduced. This situation was especially important for prehealth and biology students who might have started, but not finished, their chemistry requirements under the old model.

For the most part, the new curriculum was developed without release time. The exception is that for each academic year, coordinators for multisection laboratories received a release equivalent to teaching 1 lab section for one semester (one-twelfth of a full-time load; in principle, a full-time load at CSB/SJU is 6 lecture sections per academic year, or 12 lab sections, or an equivalent combination). An annual one-twelfth release for workbook development for the Structure and

DOI: 10.1021/acs.jchemed.6b00116
J. Chem. Educ. 2016, 93, 1383−1390

Reactivity sequence was also secured, given the fact that the workbook was the principal means of engaging students with the material. The NSF grant did provide stipends during summer for developing course materials, but the number of hours covered was minor compared to hours worked.

Fitting in the Faculty

Implementation of the new reactivity courses relied heavily on the use of instructor cohorts. The department is relatively large, effectively representing two small colleges. Faculty members with relevant training in reactivity include: one biochemist, with experience in protein biochemistry and enzyme kinetics; one inorganic chemist, with experience in bioinorganic and transition metal cluster chemistry; one environmental analytical chemist, with training in organometallic kinetics; and four organic chemists, with training in natural products isolation and synthesis; organic methodology; medicinal chemistry; and physical organic chemistry of organometallics. These faculty members either directly participated in teaching or else were available to coach other instructors.

In its first iteration, parallel sections of Reactivity I were taught by the aforementioned natural products, inorganic, analytical, and medicinal chemists. The first offering of Reactivity II was staffed by the natural products, medicinal, and physical organic chemists. These instructors frequently met as a group, and in some cases would even share quizzes, meeting to grade them together. In this way, novices in a particular area could see the kinds of questions an expert might ask, and how the expert might respond to answers that deviated from expectation. The other instructors rotated into both courses in subsequent semesters. However, note that the biochemist has taught neither of these courses (but has taught Reactivity III) despite obvious connections to the material. Nevertheless, that person has been available to meet with both faculty members and students with questions about the material. A longstanding policy in the department encourages students to seek out a variety of instructors for questions; this goal has been facilitated through the adoption of an online appointment registration system that allows students to see what instructors have experience in what course. In subsequent years, the number of instructors involved has broadened because adjunct instructors have often requested to participate in this sequence, including two organic chemists, a biochemist, and an inorganic chemist.

Other "non-Reactivity" members of the department include two physical chemists (a laser spectroscopist and a surface scientist), two more traditionally trained analytical chemists (atmospheric and biomaterials separations), and one person with experience in secondary education. These instructors participate in the introductory course, Structure and Properties; a number of foundation-level laboratories; the two Quantitation courses: Macroscopic and Microscopic Chemical Analysis; in-depth courses in their specific area of training; and interdisciplinary science courses for education or environmental studies majors. One of the physical chemists, however, is projected to participate in Reactivity I in the next year.

■ ASSESSMENT

As was the case during the introduction of both Chem 125: Structure and Properties and Chem 250: Reactivity I, the ASO (average student outcome, or average grade based on a 4.0 scale) and percent of students receiving grades of D, F, or W were documented for Chem 251.[3,4] Because of some topical overlap and the fact that most students take the course in the autumn of their second year, these results were compared against numbers from Organic Chemistry I in previous years (Table 3). Results from Organic Chemistry II are also included since Chem 251 represents a second semester working with concepts of reactivity. In general, the ASO in Chem 251 is similar to that in predecessor courses in organic chemistry. Students continue to perform at a similar level on topics related to those older courses. In addition, DFW data appear to be slightly lower than in the older courses. This might not be the case if something were not working in the new course structure.

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

Course	Students	ASO	%W	%DFW
Org Chem I AY '05-'12[b,c]	133	2.66	6.0	10.0
Org Chem II AY '05-'12[c]	100	2.62	3.5	8.9
Reactivity II AY '13[d]	108	2.84	3.7	4.6
Reactivity II AY '14[e]	103	2.86	1.9	3.8
Reactivity II AY '15[e]	112	2.82	1.0	3.9

[a]Mean grade earned in the class on a 4.0 scale. [b]AY # refers to end of academic year; that is, AY '05 = academic year 2004−2005. [c]Average number per year during period reported. [d]Spring section only. [e]Fall and spring sections.

As an additional measure of student performance, selected questions from ACS standard exams were delivered in an online format as part of the final exam in Chem 251 (Table 4). Thirty-eight questions were selected for this purpose, with the same questions presented each year. These questions were selected by an instructor who did not teach the course in its first year but who was provided with a list of topical coverage; the intent was to buffer the resulting exam against instructor bias. The results show that Chem 251 students perform similarly to their national peers (close to the 60th percentile). For comparison, during the 10-year period prior to the implementation of the new curriculum, CSB/SJU students performed well on ACS exams in organic chemistry II (average of 71st percentile nationally). This was also the case for inorganic chemistry (average of 77th percentile nationally); the ACS biochemistry exam was not used during this period. Note that typical students take the organic ACS exam at the end of their fourth semester and the inorganic exam somewhere between their fifth and eighth semester, whereas Chem 251 students are only in their third semester. Overall, these results suggest radical changes in the presentation of material do not adversely affect students' ability to perform standard tasks expected of chemistry students elsewhere.

Table 4. Comparison of Average Difficulty Index on ACS Exam Questions in Chem 251 to Nationally Normed Data[a]

	Average Difficulty Index (std. dev.)	
Year	Chem 251	National[b]
AY '13	0.60 (0.20)	0.57 (0.15)
AY '14	0.59 (0.20)	0.57 (0.15)
AY '15	0.64 (0.18)	0.57 (0.15)
Fall '16	0.61 (0.20)	0.57 (0.15)

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

DOI: 10.1021/acs.jchemed.6b00116
J. Chem. Educ. 2016, 93, 1383−1390

A broader measure of the effects of curricular change might be found in the overall experience of majors. The number of students graduating with majors in chemistry and biochemistry has increased since the new curriculum was introduced (Table 5); most students formally declare their major while enrolled in Chem 251. This change may be a sign that the topics presented in Chem 251, as well as the prerequisites (Chem 125 and Chem 250), capture the imagination of potential majors better than the topics in our previous introductory courses.

Table 5. Number of Chemistry and Biochemistry Majors Graduated

Major	AY '95–'14[a]	AY '15[b]	AY '16[c]	AY '17[c]
Chem	13	27	28	23
Biochem	7	16	17	20

[a]Average per year during this period. [b]First cohort to graduate from new curriculum. [c]Projected, based on estimated 10% attrition after declaration of major in second year.

A final index of how well these students have been trained can be seen in results from the Major Field Achievement Test (MFAT, Table 6). Data from the first class to graduate from the new curriculum were comparable to results seen in previous years. Overall, a substantial increase in the number of majors has been seen without sacrificing quality of instruction. Additional data were obtained on the Diagnostic of Undergraduate Chemistry Knowledge (DUCK); although this tool was not used in the past, it may provide other departments with a useful comparison.

Table 6. Overall Performance by Seniors on MFAT[a] and DUCK[b]

			National Percentile Score		
Test	Year	Students	High	Low	Mean
MFAT[c]	AY '04–'14	164	99	16	79
	AY '15	13	93	31	76
DUCK[c,d]	AY '15	13	97	14	60

[a]Major Field Achievement Test. [b]Diagnostic of Undergraduate Chemistry Knowledge. [c]Students randomly assigned MFAT or DUCK. [d]No baseline data available.

■ CONCLUSIONS

Chem 251 presents topics from the domains of organic, inorganic, and biochemistry together in order to provide a more unified view of reactivity across chemistry. Compared to Chem 250, which takes a similar approach, Chem 251 places more emphasis on reactions that could proceed through multiple mechanistic pathways. Kinetics is developed as a tool to gain insight into these mechanisms. Despite the introduction of these topics in a nontraditional context, students still perform well based on traditional measures such as standard exam questions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00116.

Sample pages from Reactivity II 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 thank Henry Jakubowski for helpful discussions about the course.

■ REFERENCES

(1) (a) Polik, W. F.; Larive, C. K. 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.

(2) 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.

(3) 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.

(4) Schaller, C. P.; Graham, K. J.; Johnson, B. J.; Jones, T. N.; McIntee, E. J. Reactivity I: A Foundation-Level Course for Both Majors and Nonmajors in Integrated Organic, Inorganic, and Biochemistry. *J. Chem. Educ.* **2015**, *92* (12), 2067–2073.

(5) National Science Teachers Association. The Next Generation Science Standards. http://ngss.nsta.org/AccessStandardsByTopic.aspx (accessed May, 2016).

(6) Sung, S. S.; Gordon, J. I.; Rose, G. D.; Getzoff, E. D.; Kron, S. J.; Mumford, D.; Onuchic, J. N.; Scherer, N. F.; Sumners, D. L.; Kopell, N. J. Educating Future Scientists. *Science* **2003**, *301* (5639), 1485.

(7) Van Hartesveldt, C.; Giordan, J. *Impact of Transformative Interdisciplinary Research and Graduate Education on Academic Institutions*, Workshop Report; National Science Foundation: Washington, DC, 2008.

(8) Fair, J. D.; Kleist, E. M.; Stoy, D. M. A Survey of Industrial Organic Chemists: Understanding the Chemical Industry's Needs of Current Bachelor-Level Graduates. *J. Chem. Educ.* **2014**, *91* (12), 2084–2092.

(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) Talanquer, V. Central Ideas in Chemistry: An Alternative Perspective. *J. Chem. Educ.* **2016**, *93* (1), 3–8.

(12) Gillespie, R. J. The Great Ideas of Chemistry. *J. Chem. Educ.* **1997**, *74* (7), 862–864.

(13) Atkins, P. Chemistry: The Great Ideas. *Pure Appl. Chem.* **1999**, *71* (6), 927–929.

(14) Chesick, J. P. Integrated Physical-Analytical Course. *J. Chem. Educ.* **1965**, *42* (4), 199–201.

(15) Shultz, G. V.; Gottfried, A. C.; Winschel, G. A. Impact of General Chemistry on Student Achievement and Progression to

Subsequent Chemistry Courses: A Regression Discontinuity Analysis. *J. Chem. Educ.* **2015**, *92* (9), 1449−1455.
(16) Gillespie, R. J. The Changing Roles of Descriptive Chemistry: Integrating Reactions and Properties with Theories and Principles of Inorganic and Organic Chemistry. *J. Chem. Educ.* **1994**, *71* (8), 665−666.
(17) Reingold, I. D. Inverting Organic and Biochemistry: A Curriculum Tweak that Benefits All. *J. Chem. Educ.* **2004**, *81* (4), 470−474.
(18) 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*; Duffy-Matzner, J. L., Pecheco, K. A. O., Eds.; ACS Symposium Series; American Chemical Society: Washington, DC, 2012; Vol. *1108*, pp 177−183.
(19) 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.
(20) Reingold, I. D. *Organic Chemistry: an Introduction Emphasizing Biological Connections*, 2nd ed.; Indo-American Books: Delhi, 2007.
(21) Soderburg, T. *Organic Chemistry with a Biological Emphasis.* http://facultypages.morris.umn.edu/~soderbt/textbook_website.htm (accessed May, 2016).
(22) Solomons, T. W. G.; Fryhle, C. B.; Snyder, S. A. *Organic Chemistry*, 12th ed.; Wiley: Hoboken, NJ, 2016; pp 938−964.
(23) Bruice, P. Y. *Organic Chemistry*, 8th ed.; Pearson/Prentice Hall: Upper Saddle River, NJ, 2016; pp 508−531.
(24) Johnson, B. J.; Graham, K. J. A Guided Inquiry Activity for Teaching Ligand Field Theory. *J. Chem. Educ.* **2015**, *92* (8), 1369−1372.
(25) 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.
(26) Lowery Bretz, S.; 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.
(27) Cardellini, L. Conceiving of Concept Maps to Foster Meaningful Learning: An Interview with Joseph D. Novak. *J. Chem. Educ.* **2004**, *81* (9), 1303−1308.
(28) Graham, K. J. An Improved Decision Tree for Predicting a Major Product in Competing Reactions. *J. Chem. Educ.* **2014**, *91* (8), 1267−1268 and references therein..
(29) Jones, G. R. H. Substitution Reactions in Octahedral Complexes. *J. Chem. Educ.* **1966**, *43* (12), 657−659.
(30) Cakmakci, G. Identifying Alternative Conceptions of Chemical Kinetics among Secondary School and Undergraduate Students in Turkey. *J. Chem. Educ.* **2010**, *87* (4), 449−455.
(31) Lechner, J. H. More Nuts and Bolts of Michaelis−Menten Enzyme Kinetics. *J. Chem. Educ.* **2011**, *88* (6), 845−846.
(32) Holmes, R. R. Comparison of Phosphorus and Silicon: Hypervalency, Stereochemistry, and Reactivity. *Chem. Rev.* **1996**, *96* (3), 927−950.
(33) Zohar, A. Connected Knowledge in Science and Mathematics Education. *Int. J. Sci. Educ.* **2006**, *28* (13), 1579−1599.
(34) Weaver, G. C.; Sturtevant, H. G. Design, Implementation, and Evaluation of a Flipped Format General Chemistry Course. *J. Chem. Educ.* **2015**, *92* (9), 1437−1448 and additional communications from that issue..
(35) Smith, J. D. Student Attitudes toward Flipping the General Chemistry Classroom. *Chem. Educ. Res. Pract.* **2013**, *14*, 607−614.
(36) 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.
(37) Schaller, C. P. *Structure and Reactivity in Organic, Biological and Inorganic Chemistry*. http://employees.csbsju.edu/cschaller/ROBI2.htm (accessed May, 2016).
(38) Larsen, D., ed. *ChemWiki: The Dynamic Chemistry Hypertext.* http://chemwiki.ucdavis.edu (accessed May, 2016).
(39) 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.
(40) 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.

DOI: 10.1021/acs.jchemed.6b00116
J. Chem. Educ. 2016, 93, 1383−1390