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Developing and Implementing a Reorganized Undergraduate Chemistry Curriculum Based on the Foundational Chemistry Topics of Structure, Reactivity, and Quantitation

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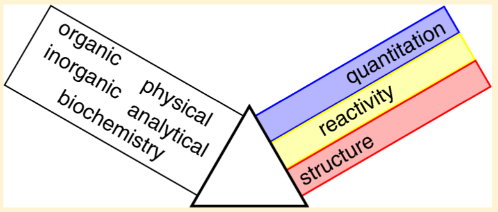
Ⓢ *Supporting Information*

ABSTRACT: The recent revision of undergraduate curricular guidelines from the American Chemical Society Committee on Professional Training (ACS-CPT) has generated interest in examining new ways of organizing course sequences both for chemistry majors and for nonmajors. A radical reconstruction of the foundation-level chemistry curriculum is presented in which content has been reorganized into three sequences: structure, reactivity, and quantitation. It is proposed that these three areas represent fundamental aspects of chemistry that cross traditional domains and allow students to more quickly appreciate the breadth of the field. An overview of these sequences in the chemistry curriculum at CSB/SJU is described.



KEYWORDS: *Curriculum, Interdisciplinary/Multidisciplinary, First-Year Undergraduate, Second-Year Undergraduate*

INTRODUCTION

There is considerable interest in examining new ways to deliver the chemistry curriculum. Much of the activity in this area has been directed at significant improvements in classroom teaching methods.[1,2] Relatively little has changed in the content of chemistry courses over the years, however.[3,4] The recent revision of guidelines from the American Chemical Society Committee on Professional Training (ACS-CPT) has allowed chemistry programs to consider anew how best to instruct their students by moving away from a prescribed set of courses for an ACS chemistry major.[5] Calls for reform have been spurred by the nature of chemists' work in research and industry, which is less compartmentalized than might be suggested by a delivery of the curriculum in courses based on the traditional five subdisciplines of analytical, physical, inorganic, organic, and biochemistry.[6] A curriculum composed of a laundry list of topics often fails to meet the needs of majors and nonmajors alike.[7] Educational changes outside of chemistry, most notably in the premedical curriculum, have also contributed to re-evaluation.[8]

The ACS-CPT guidelines allow varying degrees of innovation. Although "foundation-level" courses are now required to cover the five traditional subdisciplines, specific courses in each area are not mandated, as long as these courses provide the equivalent of one semester of coverage of each subdiscipline.[5] Furthermore, the nature of the "in-depth" courses is not prescribed, but may meet the strengths and needs of individual departments. Some departments may choose to make minor modifications to their undergraduate programs, whereas others may adopt an entirely new system. Given the latter possibility, there is a pressing need for vigorous discussion of new models that may guide the development of new curricula.[3,9,10] We seek to outline such a model here, based on studies of structure, reactivity, and quantitation. Our purpose is to promote discussion on this matter, and we hope that our ideas will be met with counterproposals from other quarters. However, we are in the process of implementing our new chemistry curriculum at College of Saint Benedict/Saint John's University (CSB/SJU) entirely on these principles. Although we do not wish to be prescriptive, we will provide some illustrative details from our own experience as appropriate. More complete descriptions of individual courses in our own curriculum will be communicated in the future.

NEW MODELS FOR CHEMISTRY

A very thoughtful proposal by Goedhart included a brief history of chemical education and sought to completely reorganize chemistry instruction into three new areas: analysis, synthesis, and theory development.[9] *Analysis* included, for example, the composition of mixtures investigated in analytical chemistry as well as structure determination as typically practiced in organic chemistry. *Synthesis* included organic products and materials science. *Theory development* involved both numerical and qualitative modeling.

Philosophically, Goedhart seeks to reorganize undergraduate chemistry instruction based on what he sees as the three most basic tasks of practicing chemists. However, there are certainly other ways in which we could reclassify chemical studies; in the interest of furthering this discussion, other viewpoints should be developed. One alternative version would be based on *structure*, *reactivity*, and *quantitation*, three fundamental aspects of chemistry.

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Typical of most sciences, chemistry is predictive, often quantitatively so, and quantitative models occupy a key role in the discipline. However, as the study of matter, chemistry is deeply rooted in considerations of the structure of matter on the atomic and molecular scale. It is also distinguished from other disciplines by its paramount concern for chemical reactions. Thus, structure and reactivity are at the heart of chemistry.[11] This frame of reference places an emphasis on the fundamental nature of the field of chemistry. By getting immediately to the crux of what chemistry is all about, we can quickly define key aspects of the discipline and lay out story lines dealing with chemistry that are appealing, have obvious relevance to daily life, and reinforce basic concepts. In doing so, an emphasis should be placed early on in building an understanding of why things happen, rather than training students to carry out specific tasks.[12] In this way, we may naturally build on students' knowledge and gradually bridge to more abstract ideas.

Our contention is that chemistry is the study of the material world, with its diversity of structures and transformations. An understanding of the structures of matter, at or above the atomic level, is one of the fundamental goals of chemistry. So too is the study of reactivity: an understanding of how and why reactions take place. At a deeper level, these studies must address how we gather evidence and develop pictures of what is happening on this invisible scale. A good deal of that evidence involves mathematical models and quantitative reasoning, an area that has long been seen as a cornerstone of modern chemistry. This area must be addressed fully, although it need not be tackled at the beginning of the curriculum.

To a student first entering the study of chemistry, it seems natural to begin at the first and simplest definition of chemistry. Chemistry is the study of matter. What is matter? Matter is the substance that makes up the physical world around us. It is based on some simple building blocks, but the many ways in which those blocks can be assembled leads to a great complexity of structures. Those structures are directly responsible for the properties of each material. Materials as different as metals, plastics, water, and plants are part of the novice students' familiar world; these items and others form obvious access points to pursue basic questions about structure.

Structure in itself is therefore interesting enough, but materials in nature are seldom static. Under certain circumstances, one material with a given set of properties becomes transformed into another. Matter undergoes chemical reactions. Structure and reactivity are two cornerstones of modern chemistry. How these reactions occur, the sparks that start them, the engines that drive them, and the pathways that lead them forward are questions that have occupied a significant fraction of chemical investigation during the past century. Developing an understanding of the rules and patterns of chemical reactivity is a central task for any student of chemistry or biochemistry. Furthermore, learning to decipher empirical evidence of how a reaction has happened takes students further down the path toward thinking like scientists.

Some of the evidence for how reactions take place comes in the form of numerical data, and mathematical models are frequently used to interpret such information. Aspects of quantitative reasoning can be found throughout chemistry, and consequently students should have explicit training in this area. Numerical approaches are found in the analysis of samples, in which we try to determine the content of materials, as well as in building predictive models for quantifiable behavior of materials. Nevertheless, an introduction to these tasks might be best delivered separately from a consideration of structure and reactivity, simply because this aspect of chemistry asks students to conceptualize in a different way. In presenting both qualitative and pictorial models at the same time as quantitative ones, students may be tempted to give up on one model as soon as they have grasped the other.[13]

For example, when the concept of equilibrium is typically introduced in general chemistry, students are still developing ideas of structure and have hardly had any experience with reactions. Suddenly they are expected to understand what is happening in a reaction, to grasp that the reaction is a system involving many participants moving in both directions, to see that energetic differences are involved, and to be able to quantify the exact concentration of specific reactants under any one of several different scenarios. In asking students to master this set of tasks, we force them into a juggling act in which they must familiarize themselves with several different ways of thinking about equilibrium at the same time. We are lucky if they emerge with even just one of these concepts, rather than dropping them all.

At this point we should make an explicit distinction between our proposal, the curriculum proposed by Goedhart, and the chemistry curriculum as practiced over the last 50 years. Since the 1960s, a typical chemistry major in the United States, in addition to general chemistry, has usually consisted of two semesters of organic chemistry, two semesters of physical chemistry, one or two semesters of analytical chemistry, and possibly a semester each of biochemistry and inorganic chemistry. The two semesters of physical chemistry are divided into thermodynamics and quantum mechanics, whereas the two semesters of analytical chemistry are cleaved into classical and instrumental analysis. One of the problems with this approach is that its extreme compartmentalization, although perfectly sensible from an organizational point of view, can be a barrier to the efficient practice of chemistry. In the research forum, more and more applications draw on multiple subdisciplines, but students may not be able to grasp such integration until after they have completed a major.

Goedhart condenses chemistry into three different areas that correspond more closely to how chemistry is practiced. Chemists make things, whether they are inorganic or organic chemists, and these shared concerns are housed in synthesis. Chemists want to know what things are made of, whether that means determining the structure of a molecule or the composition of a solution, and these ideas are found in analysis. Chemists want to understand and predict behaviors of matter and use a variety of qualitative and quantitative models to do so; that is theory development.

In our curricular model, we seek to build on Goedhart's approach but shift the perspective from the chemist to the novice learner. The new student has no inherent interest in what chemists do. The different practices of chemists offer no vantage point that will gain the attention of a nonscientist. In contrast, everyone has experience with the world around us.[14,15] Anyone can understand that metal is different from plastic. Anyone can be engaged in the study of structure, because it brings back that gee-whiz fascination with everyday things that initially attracts many students to science.[16]

It may well be that the currently widespread approach to the chemical curriculum is simply the best way to arrive at an understanding of chemistry, and ought to be preserved. However, a choice made without the consideration of alternatives is hardly rational. We hope that the proposal made here will be followed by others in the literature, so that the community can have a robust discussion of how to describe chemistry in individual courses suitable for the 21st century.

■ OVERVIEW OF CORE AREAS

To begin, we should brainstorm about some of the individual topics that might be addressed within the areas of structure, reactivity, and quantitation. Some key concepts of these three core areas are summarized in Tables 1−3. The columns are not meant to imply different courses within each area, but are simply one way of casting the net to find topics that reasonably fit in this area.

Table 1. Key Concept Areas within the Area of Structure

Periodicity and Bonding	Three-Dimensional Structure	Structure−Property Relationships
Periodic trends	Metallic solids	Intermolecular attractions
Ionic bonding	Ionic packing	Lewis acid−base
Covalent bonding	Network solids	Brønsted acid−base
Metallic bonding	Isomerism	Malleability
	Stereochemistry	Conductivity
	Conformation	Cleavage properties
	Biomacromolecules	Glass transition

We take structure to be of fundamental importance, illustrated by the central role of structure−property relationships in chemistry and biochemistry. The rise of the "atoms-first" curriculum within general chemistry courses is a testament to the way in which other topics naturally build upon structure. However, some fundamentally important elements of structure are not always included in general chemistry. These subjects include stereochemistry and conformational analysis, the structure of metals, ionic solids, network solids, biomacromolecules such as proteins, and supramolecular assemblies. A working knowledge of these topics opens up a great deal of understanding of modern chemistry.

We have devoted the first course in our own chemistry sequence to structure−property relationships across the discipline of chemistry. All of the key concept areas are incorporated in a one-semester course that is similar to an "atoms-first" treatment.

Chemical reactions have always been at the heart of chemistry. Reactivity addresses the mechanisms and consequences of chemical change. Ideally, courses in reactivity would illustrate similar principles across organic chemistry, inorganic chemistry, and biochemistry, three different arenas in which reactions play a central role. The principles of Lewis acid and base interactions are of paramount importance, extending throughout the reactions of coordination compounds and most of organic chemistry. Conversely, electron transfer, radicals, photochemistry, and pericyclic reactions are also essential to the knowledge base of a chemist, although they exist largely beyond the realm of Lewis acid and base considerations. At CSB/SJU, we have implemented a three-course lecture sequence for the development of these ideas.

In speaking of quantitation, we refer to the numerical aspects of chemistry, both empirical and predictive. Measurement and instrumentation are the crucial concerns of a large fraction of chemists who enter the workforce directly after completion of their undergraduate studies. Together with mathematical descriptions of kinetics, thermodynamics, and quantum mechanics, which allow deeper insight into the numerical behavior of compounds and reactions, these topics have long held a primary position in the curriculum. Our approach centers on an understanding of structure and reactivity while introducing more conceptual yet timely mathematical descriptors within that context. This logical progression, implicitly recognized in "atoms-first" approaches adopted by many texts, moves a historically "mathematics-first" approach until later when the concepts of structure and reactivity are more firmly in place.[17,18] Our own curriculum at CSB/SJU features a two-course sequence in this area, and an example from one of these courses may illustrate how concepts from traditional subdisciplines of physical and analytical chemistry may support each other. Traditionally, the analytical textbooks derive the equilibrium constant expression from the law of mass action. The derivation is based on the idea that the forward and the reverse rates of a reaction at equilibrium must be equal. In the new curriculum we develop the laws of thermodynamics up through the definition and properties of free energy functions. The goal is to develop the unified view of equilibrium and the direction of spontaneous change in terms of chemical potentials of substances. The students then apply their knowledge by doing equilibrium problems and calculations.

Table 3. Key Concept Areas within the Area of Quantitation

Quantum Theory	Thermodynamics	Chemical Equilibrium
Wave functions	The distribution of molecular states	Molar relationships
Translational, vibrational, and rotational motion	Enthalpy	Equilibrium concentrations
Atomic and molecular spectroscopy (absorption and emission)	Entropy	Phase distribution equilibrium
Computational chemistry	Free energy	Surface chemistry
	Direction of spontaneous change	Instrumental measurements

■ SOME ADVANTAGES OF STRUCTURE/REACTIVITY/QUANTITATION

This new system of course classification offers distinct advantages. By breaking down walls between traditional subdisciplines, we can tell a more continuous story.[19] Whereas

Table 2. Key Concepts within the Area of Reactivity

Lewis Acids and Bases	Single Electron Reactions	Studies of Reactivity	Applications of Reactivity
Substitution in coordination complexes	Oxidation and reduction	Kinetics	Enzymes
Nucleophilic aliphatic substitution	Radical chain reactions	Thermodynamics	Biochemical pathways and regulation
Nucleophilic π systems	Photochemistry	Reactive intermediates	Organometallic catalysis
Addition to carbonyls			Drug design
Substitution at carbonyls			

a typical general chemistry course might jump from Lewis structures to gas laws, for example, a structure course would focus on the development of periodic trends, bonding, and spatial relationships that build on each other. Topics may also build from course to course as illustrated in Figure 1. For example, elements of molecular orbitals might be introduced in structure, used qualitatively to explain reactivity, and developed mathematically in quantitation.

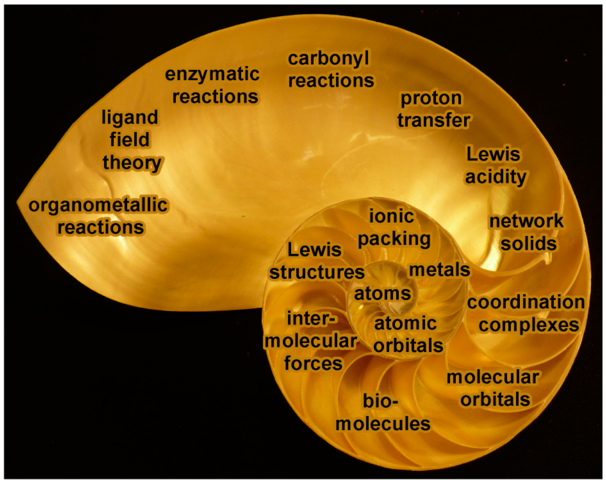

Figure 1. Example of how topics might be linked between a course in structure (inner spiral) and a course in reactivity (outer spiral). Topical lines of reasoning radiate outward from the center of the nautilus shell, but also progress from the center in a spiral manner.

By blending traditional areas, we can place a spotlight on topics that enjoy vigorous research attention, such as bioinorganic chemistry or metal organic frameworks. Topics such as these can be presented as case studies to illuminate how different aspects of chemistry are brought together to address one problem. Instead of marching students through chemistry in rigid columns, they can sample more diverse offerings, so that an individual student is more likely to encounter appealing topics within a course subject. Some students who lean more toward biological topics will be intrigued by the biochemical illustration of chemical principles, whereas those who find more fascination in technology may be more interested in examples from materials science. That interest will translate into enhanced learning and retention.[20] Furthermore, students can start to see where their own interests may fit in the research lab from an early point, facilitating a good match between undergraduate researchers and appropriate advisors.

By transitioning to a three-layered presentation, we can more easily convey the message that different areas of chemistry depend on each other. In effect, we lead students through a logical sequence with inherent appeal to chemists by asking, "What does this material look like? How does this material behave? What quantifiable predictions can I make about that behavior?" Rather than specializing in one course within chemistry, students will see that all three areas play a role in most applications in the workplace and research arena.

This reorganization does not have to be rigorously enforced. For example, concepts of Lewis and Brønsted acid−base chemistry can serve as a capstone to a course in structure. Although these topics are truly elements of reactivity, they serve as excellent illustrations of structure−property relationships and so they build a natural bridge from the foundation of intermolecular attractions to a subsequent course in reactions. Similarly, some discussion of enthalpy and entropy naturally arises in the context of reactions that occur in equilibrium, and a simple approach to the temperature dependence of free energy would be appropriate within a reactivity course. Some principles of kinetics likewise fit well in the framework of reactivity, and graphical approaches to rate laws and enzyme inhibition are obvious additions to such a course. In general, case studies can be excellent ways of conveying concepts in context, and often lend themselves to the integration of multiple aspects of a discipline to address a problem.[21,22]

Part of the reason for introducing more qualitative concepts of structure and reactivity before exclusively mathematical treatments is because of the more abstract nature of the latter. Too often, graceful mathematical descriptions become routinely algorithmic if students do not grasp the ideas behind them.[23,24] Although much of chemistry occurs on a scale beyond everyday experience, deeply mathematical approaches quickly become the means and the ends themselves, even if they resist analogy and interpretation. These tools may best be reserved for experienced learners who are motivated to grapple with more abstract challenges. We frequently lose sight of that fact because, as highly successful chemistry students ourselves, few of us struggled greatly with quantitative aspects of the subject until they approached the apogee of sophistication. For many students, the barrier to dealing with mathematics is reached much sooner. The intent of this curricular approach is to build receptivity to more sophisticated approaches, so that students will have a firmer goal in mind when the time comes to be proficient in predicting and measuring chemical phenomena.

That is not to say that the structure and reactivity portions of this curriculum should be without rigor. We should not make the mistake of thinking that the only challenging aspects of chemistry are based in calculus and algebra. Reportedly, students do feel challenged by qualitative aspects of organic chemistry, for example, especially when expectations extend beyond rote memorization to questions of synthesis, mechanisms of unfamiliar reactions, spatial reasoning, and data analysis, including spectroscopy. Guidelines such as Bloom's taxonomy can be employed in an effort to ensure that high standards are preserved in the classroom, whether the material is explicitly mathematical or not.[25]

■ IMPLEMENTATION OF CURRICULAR CHANGE AT CSB/SJU

Our primary aim in this article is to promote a discussion of alternative approaches to the organization of chemistry, rather than to provide a single template for adoption by others. Nevertheless, readers will reasonably ask what such a reorganized field might look like in practice. Thus, some details about our own curriculum are warranted, although considerations of space dictate that elaboration of individual courses should be reserved for future communications.

An overview of the CSB/SJU chemistry curriculum is provided in Figure 2. The curriculum is guided by the ideas we have presented, although in some situations we have further hybridized between these three broad areas, drawing elements from one area into a course that is mostly focused on another.

The prefoundation course is devoted to the study of structure, as we consider that to be the fundamental basis of other topics in chemistry. Our one-semester introductory course is Principles of Chemical Structure and Properties.

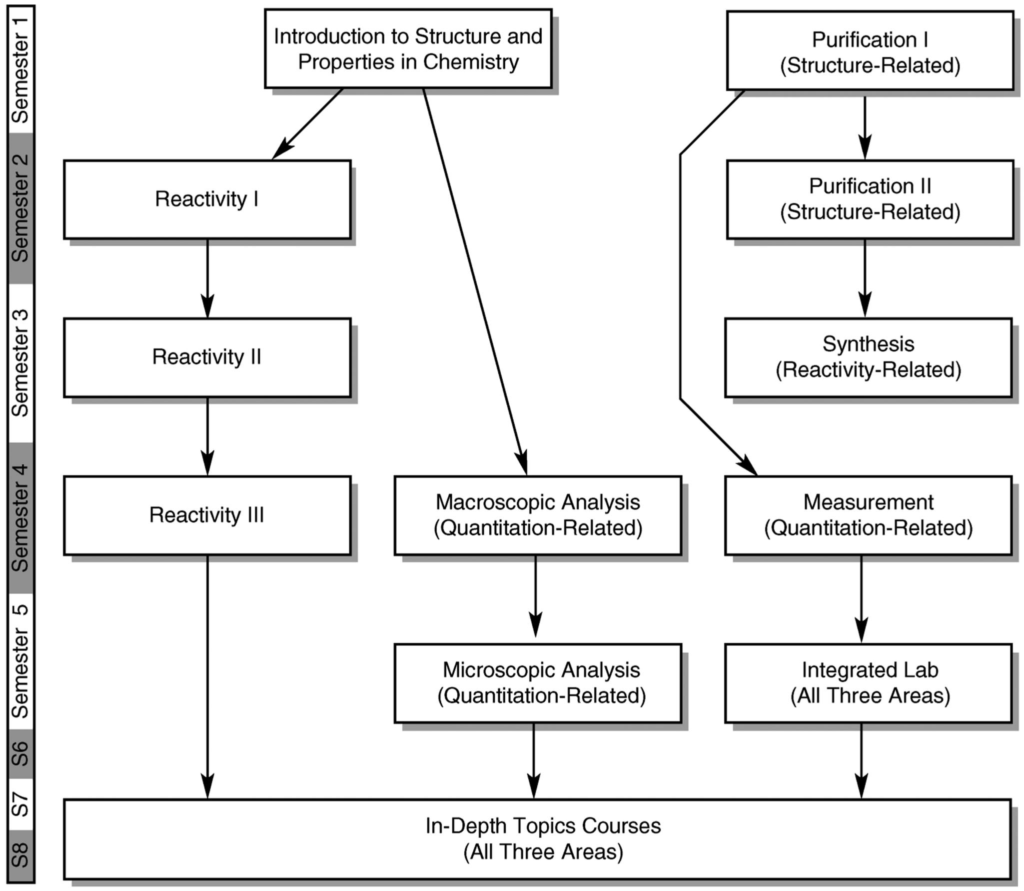

Figure 2. Overview of revised chemistry curriculum at the College of Saint Benedict/Saint John's University.

Afterward, almost all students proceed to a two-semester sequence in reactivity, which form the first two of the five foundation courses recommended by ACS-CPT.

The overall goal of Reactivity I is to provide enough background in organic carbonyl chemistry and inorganic coordination compounds so that students can look mechanistically at the basic metabolic pathways: glycolysis and gluconeogenesis, the citric acid cycle and fatty acid biosynthesis. Biochemistry thus acts as a unifying theme in this course.[26,27] Qualitative concepts of thermodynamics are introduced in the form of driving force and simple entropy considerations, and Le Châtelier's principle is addressed in reversible reactions.

In Reactivity II, students begin to see how chemists arrive at an understanding of reaction mechanisms. They look at some unimolecular and bimolecular reactions involving coordination compounds and alkyl halides. These examples highlight the difference between the prediction of mechanistic pathways based on structure and reaction conditions and experimental evidence for a mechanistic pathway, such as rate data. Kinetic considerations are also extended to a development of the Michaelis–Menten model and enzyme inhibition studies.

Most students then move to Macroscopic Analysis, our first course in the area of quantitation. We will, however, allow students who are keenly motivated by mathematics to enter this course directly after Principles of Chemical Structure and Properties. Macroscopic Analysis presents a treatment of equilibrium from a thermodynamic perspective; this foundation is then used to build a discussion of analytical methods, including titrations and electrochemical analysis.

The remaining foundation level courses include Reactivity III and Microscopic Analysis. Reactivity III addresses non-Lewis acid–base chemistry, especially the single electron events in redox and organic radical chemistry, as well as photochemistry. These topics allow coverage of a number of biochemical systems, including photosynthesis and oxidative phosphorylation and nitrogen fixation. Pericyclic reactions are also presented in this course. Reactivity III can be taken after Reactivity II, and many chemistry and biochemistry majors have taken it concurrently with Macroscopic Analysis in order to leave their schedules more flexible in their third year for study abroad or other courses.

Microscopic Analysis, a projected second course in the area of quantitation, is currently under development for introduction in academic year 2014–15. It will address questions of quantum mechanics, its applications in spectroscopy and computational chemistry, and aspects of instrumental analysis that involve spectroscopic techniques.

In addition to these foundation-level courses, chemistry majors will take additional in-depth courses focusing on the application of foundation-level material to a variety of special topics. Specific courses will be introduced into the curriculum over the next two years. These students also take supporting courses in mathematics and physics. We frequently recommend that chemistry majors also take some biology, although it is not required. Chemistry minors currently take all five foundation courses.

Biochemistry majors will take introductory biology, four chemistry foundation courses (all except Microscopic Analysis), and a combination of chemistry in-depth courses and biology courses, including Biochemistry, Cell Biology, and Molecular Genetics.

Laboratory Curriculum at CSB/SJU

For a number of reasons that are not central to this discussion we have adopted laboratory courses that are formally separate from our classroom courses. There is certainly nothing to prevent the adaptation of existing experiments from organic, inorganic, and biochemistry to accompany a course such as Reactivity III, but that is not the route that we have taken.

Our laboratory curriculum focuses on skill development and data analysis, preparing students for research as well as a general sense of laboratory independence. In addition, we have found that some concepts traditionally addressed in lecture can be introduced in dry lab situations.[28] Our first course is Purification and Separation Laboratory (Purification I). This course introduces students to basic lab skills such as weighing and filtration. Instruction is given in infrared (IR) and nuclear magnetic resonance (NMR) spectroscopy before students proceed to some benchtop purification techniques: sublimation, distillation, recrystallization, solvent partitioning, and acid−base extraction. Additionally, students use gas chromatography (GC) via an autosampler, comparing results to a table of standard retention times. In each case, students work independently with an unknown sample selected from a list in the lab manual. Students must develop an argument about the identity of the sample and its purity.

In Purification and Chromatography Laboratory (Purification II), the format is similar to that of Purification I, beginning with a dry lab introduction to ultraviolet−visible (UV−vis) and mass spectrometry (MS). Students perform thin-layer chromatography (TLC) on silica as well as column chromatography experiments using a silica column, ion exchange, reverse phase, size exclusion, and a protein affinity gel. Additional characterization of the latter experiment is obtained by running a polyacrylamide gel electrophoresis (PAGE). A further variation is performed by carrying out an enzymatic resolution of two enantiomers, followed by chromatographic purification. Students continue to practice spectroscopic techniques from Purification I.

In Synthesis Lab, students receive instruction in additional techniques such as ^{31}P and two-dimensional (2D) NMR. We have also found it convenient to work on ideas such as moles, equivalents, and concentrations, frequently employed in the context of a synthetic procedure. Projects include the reduction of a carbonyl compound, a carboxylic substitution reaction, ring-opening polymerization, synthesis of a coordination complex, formation of a fluorescently labeled liposome, and expression of a fluorescent protein. Students also work with a partner to choose a reaction procedure to follow from the literature and modify the procedure to be more environmentally benign.

In Measurement Laboratory, students develop a number of skills crucial for gathering and understanding reliable data. Students learn to perform calibrations, develop an understanding of Beer's law, carry out titrations using both electrochemical colorimetric detection, determine the concentration of an unknown protein and the vapor pressure of a pure liquid, and learn to assess error by using statistics.

Chemistry majors continue on to an Integrated Laboratory. After an introduction to electronics, students work in computational chemistry with organic, inorganic, and biochemical structures; perform enzyme kinetics and examine protein−substrate interactions; investigate metal binding to deoxyribonucleic acid (DNA) and metal-catalyzed alkene isomerization; analyze the products of the photolysis of pharmaceuticals; and perform an experiment with a Schlenk line. Students also plan and carry out a simple three-step organic synthesis. These experiments are supported by a variety of analyses, including NMR, IR, UV−vis and fluorescence spectroscopy, mass spectrometry, cyclic voltammetry, magnetic susceptibility, GC, and high-performance liquid chromatography (HPLC).

Biochemistry majors and premedical students take the first four laboratories in this sequence. Chemistry minors currently take four foundation laboratories, but not the integrated lab. Currently, biology majors take the Purification laboratories, proceeding further only if interested in prehealth professions. Nursing and nutrition majors do not take any laboratories.

Curricular Innovation and Transfer Students

We should note that there is a fundamental conflict between concern for transfer students and a thorough examination of how to structure the chemical curriculum. One of these goals, in an ideal case, dictates perfect congruity between the curricula at two different schools and by extension at all other schools. The curriculum remains static in perpetuity. The other goal necessitates either a top-down command giving specific, revised requirements from ACS-CPT or else isolated innovation by one school or a subset of institutions small enough to coordinate their curricular activities.

In seeing the need to institute new guidelines, ACS-CPT clearly tilted away from the first goal. In its 2008 announcement of these guidelines, representatives of ACS-CPT explicitly stated a desire to promote curricular innovation based in individual chemistry departments. That outlook seems sensible in light of myriad, independent developments in pedagogy over the past few decades, including process-oriented, guided-inquiry learning (POGIL), peer-led team learning (PLTL), problem-based learning, and so forth. Although we must be empathetic in aiding transfer students to adapt to a change in schools, the benefit of a free market process to develop new approaches to teaching chemistry clearly outweighs the need for uniformity.

At CSB/SJU, we work with relatively few transfer students and so these situations can be handled on a case-by-case basis. In some instances, students with partial overlap in course coverage have joined a course section for a portion of the semester as part of the requirement for an independent learning project. Additional details of our policy are provided in the Supporting Information. As would be expected, there is not a one-to-one correspondence between our courses and those of other schools, but substitutions are made for individual courses or groups of courses where appropriate. Students may end up "behind" a semester in certain situations. That outcome is preferential to allowing a student to proceed with too many gaps in their knowledge, in our experience. In fact, the latter situation sometimes occurs even in a standard curriculum when a student divides a two-semester sequence in chemistry, biology, or physics between two different schools.

We have explicitly tried to mitigate the negative effects of curricular change on transfer students or late starters by introducing trailer sections for all introductory- and foundation-level courses and laboratories. Thus, all of these courses are offered during both spring and fall semesters. As a result, a student may be behind by only a semester rather than waiting an entire year for the opportunity to catch up.

Curricular Innovation and Preprofessional Students

Preprofessional students face issues similar to those of transfer students. In both cases, students request that a set of courses completed at one school should satisfy requirements at another.

Premedical students merit special attention here, both because of the relatively large numbers of these students in many chemistry courses and because of the reorganization of science requirements as defined in the Medical College Admission Test (MCAT). We have found that many medical schools are moving away from specific course requirements in chemistry. As a result, chemistry proficiencies for premedical students are more strongly linked to MCAT than ever before. In our curriculum, these students take Principles of Chemical Structure and Properties, Reactivity I and II, then Macroscopic Analysis. This sequence is similar in approach to a "1-2-1" curriculum in which students take a semester of general chemistry, two semesters of organic chemistry, and a semester of general or analytical chemistry. That approach can also be seen as an overview of basic chemical concepts followed by a study of (strictly organic) reactivity and capped with quantitative work.

Additional details of our recommendations for preprofessional students at CSB/SJU as well as MCAT coverage in the sequence for premedical students are provided in the Supporting Information.

■ CONCLUSIONS

In summary, we have presented a new curricular model based on courses in structure, reactivity, and quantitation. In contrast to the approach commonly employed in undergraduate instruction, it presents a more unified view of how traditional subdisciplines of chemistry relate to each other. This treatment is also an alternative to the Goedhart model, with a stronger emphasis on the distinctive concerns of the field of chemistry. Although other nascent models surely deserve consideration and debate, we argue that this approach is well suited to build naturally from the most basic concepts of chemistry to the most sophisticated. Key elements of this model include the ability to introduce students to multiple traditional fields concurrently, the construction of a coherent story based on the basic principles of chemistry, and the illustration of how a chemist deals with different levels of a system to attain different goals.

In our approach, students first become aware of a range of considerations involving structure, including the structure of atoms, metals, ionic solids, network solids, small molecules, and biomolecules. Second, students continue to explore concepts of chemical reactivity by looking at reactions of carbonyls in organic, inorganic, and biochemistry, with some emphasis on thermodynamics and equilibrium. Additional work in substitution (ligand substitution and aliphatic nucleophilic substitution) and other reactions is developed along with some understanding of kinetics. Third, students discover the crucial role of mathematical reasoning in chemistry through courses in quantitation. The latter courses include both macroscopic considerations (thermodynamics and equilibrium) and microscopic concerns (quantum mechanics, computational chemistry, and spectroscopy).

The lack of alignment between any new curricular model and available textbooks is a major barrier to change; faculty who wish to make dramatic innovations face a monumental task.[29] However, the time has come when custom publishing and online homework support systems may give instructors flexibility to adopt deeply innovative approaches. We are currently implementing new courses based on this classification system in our own curriculum. We will continue to report on these new developments in the future.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Course descriptions; MCAT coverage; policies for transfer students; course recommendations for preprofessional students; preliminary assessment data; description of further supporting materials for structure and reactivity courses.This material is available via the Internet at http://pubs.acs.org.

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Notes

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