JOURNAL OF CHEMICAL EDUCATION

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Chemical Structure and Properties: A Modified Atoms-First, One-Semester Introductory Chemistry Course

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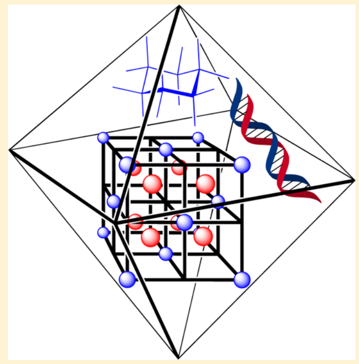
Supporting Information

ABSTRACT: A one-semester, introductory chemistry course is described that develops a primarily qualitative understanding of structure−property relationships. Starting from an atoms-first approach, the course examines the properties and three-dimensional structure of metallic and ionic solids before expanding into a thorough investigation of molecules. In addition to bonding, geometry, molecular orbitals, and intermolecular attractions, other structural topics are included, such as stereochemistry, conformation, and factors that influence the strength of Brønsted acids. Where appropriate, related considerations in biochemistry are highlighted. The course provides a common basis to majors and nonmajors for further study in chemistry and also serves as a platform to illustrate a variety of topics of current research interest.



KEYWORDS: *First-Year Undergraduate/General, Curriculum, Atomic Properties/Structure, Molecular Properties/Structure*

INTRODUCTION

The general chemistry course is sometimes criticized as a collection of disparate elements that do not serve introductory students as well as they should.[1] There is widespread interest in developing approaches that would bring more relevance and a clearer storyline into this course. For example, the rise of "atoms-first" textbooks over the past decade has been a striking trend in general chemistry.[2] Atoms-first general chemistry has been described as the development of introductory chemistry through the properties of atoms and molecules, rather than a traditional approach that begins with macroscopic, and often mathematical, models.[3] The atoms-first approach has been linked with a slightly stronger level of student performance during the first semester, perhaps because it delays mathematical treatments until later.[3]

Nevertheless, in seeking to reserve time for the typical components of general chemistry, an opportunity is lost to develop the full narrative of structural concerns that begins with a discussion of atoms, ions, and molecules. Additional focus on the structure and properties of molecules might better prepare students for organic chemistry in the second year, helping to bridge a difficult transition,[4] but even in an atoms-first course, momentum on these topics is usually lost in a pivot to mathematical chemistry.

In response to this problem, a number of approaches have been introduced that seek to fold different aspects of organic and biochemistry into the first year chemistry curriculum.[5−9] These curricula are, in part, fulfilling demands made by student interest in health professions and biological sciences. A focus on organic or biochemistry allows these courses to present a more coherent narrative. At the same time, their aim is to provide a foundation for later study in other aspects of chemistry. In fact, beginning the chemistry curriculum with organic chemistry, rather than the traditional general chemistry, can add later scheduling flexibility for students to take additional courses in other domains, such as inorganic, analytical, and physical chemistry.[9] This factor should not be dismissed, because it potentially has a very real impact on the numbers of skilled chemistry majors produced for the workforce.

These "early organic" approaches, such as the atoms-first approach, are laudable methods of responding to the needs of current students. In the interest of encouraging innovation through the introduction of additional curricular tools, a one-semester introductory chemistry course should be considered that blends aspects of both atoms-first and organic-first courses. This course could be thought of as an introduction to aspects of chemical structure and properties from across different domains of chemistry. This idea of structure as a cornerstone for understanding chemistry has been described elsewhere.[10] Subsequent courses would address concepts of chemical reactivity and quantitative modeling and measurements.

The wide footprint of structure across current chemistry can be illustrated by looking for it in a traditionally macroscopic and numerically oriented field such as physical chemistry. In general, there has been an increased emphasis in recent years on building conceptual understanding and connections

Published: November 17, 2014

between physical chemistry and other domains of chemistry. The latter aim serves to illustrate the broad supporting role played by physical chemistry across the rest of chemistry, engineering, and materials science.[11] Modern courses in physical chemistry have adopted concerns such as stereochemistry and racemization in amino acids and proteins;[12] molecular dynamics in protein folding;[13] cis−trans isomerism in peptides;[14] conjugation in organic molecules;[15,16] allotropism in the kinetics of ozone formation;[17] structure−property relationships in polymers;[18] and the general structure of organometallic complexes.[19] These topics, used as vehicles for the delivery of more sophisticated concepts in kinetics, thermodynamics, and quantum mechanics, rest on fundamental considerations of structure.

Where does a structure-centered introductory course fit into a perspective gleaned from educational research? Some scholarly work has tried to describe chemistry teaching in terms of three coordinates: symbolic, macroscopic, or sub-microscopic (sometimes alternatively described as particulate).[20] The sub-microscopic or particulate aspect of chemistry has traditionally been introduced very early to novice learners. Although this starting point is obvious to experienced chemists, it does not always lead to success for students.[21] Part of the difficulty for students may involve the complete gear-shifting between macroscopic, microscopic, and symbolic levels of thinking about chemistry that take place during a single semester of general chemistry, without allowing students time to appreciate the relationships between these levels. Furthermore, translating particulate concepts into useful models for studying chemistry does require the adoption of abstract representations such as Lewis structures and other drawings. The same is true for macroscopic topics, which inevitably lead to symbolic representations in mathematical approaches. An atoms-first approach might partly be understood as an attempt to simplify things by staying on the particulate-symbolic continuum and introducing the macroscopic coordinate in later courses. That limited focus may allow more careful development of the transition from particulate ideas of matter to symbolic representations. Certainly there are ways to guide this step. For example, the early use of pictorial representations of the particulate nature of matter has been demonstrated to increase student understanding of chemistry concepts at the introductory level.[22] The goal of an introductory course in structure would be to provide repeated exposure to particulate concepts of matter and their symbolic representations. Hopefully, this approach would provide sufficient practice so that students could solidify their understanding of these related ideas.

We have developed a unique first semester introductory chemistry course that attempts to lead students through the entire story of structure, from the periodic table through molecules and macromolecules in the spheres of organic and inorganic chemistry and biochemistry. At the same time, a strong emphasis is placed on structure−property relationships, a topic that is central to chemistry but which proves a struggle for many students.[23] The goal of the course is to provide a solid groundwork that will help students address questions about structure from across chemistry and biochemistry. The course is also meant to prepare students for further study in any of the subdisciplines of chemistry.

■ COURSE OVERVIEW

Context of the Course

Chem 125: Structure and Properties was conceived as a one-semester introductory course in chemistry that would serve chemistry and biochemistry majors as well as other students, including prehealth professions students. At College of Saint Benedict/Saint John's University (CSB/SJU), Chem 125 provides the background for further study in an integrated sequence built around reactivity in organic and inorganic chemistry and biochemistry.[10] After two semesters in that sequence, most students interested in biology and the health professions take a course in thermodynamics, equilibria, and analysis (similar to a 1−2−1 sequence),[6] although chemistry majors also take a third course in integrated reactivity.

In our department, students register for laboratories separately from lecture courses. This system has helped to improve flexibility of scheduling and is more accommodating to other departments. For example, nursing and nutrition/dietetics recently added Chem 125 to their major requirements. These departments specifically require the lecture without laboratory, because their previous experience suggested a laboratory component was not helpful enough to their students to justify the additional workload it entailed. However, the vast majority of students in Chem 125 are also enrolled in an introductory-level laboratory course, Chem 201: Structure and Purification. In Chem 201, students are introduced to a variety of techniques for purification and analysis of organic and inorganic compounds. Nevertheless, given the scale and complexity of the curricular revisions we have undertaken, this work will not address laboratory instruction in detail, which will be discussed in more depth at another time.

Summary of Course Content

Chem 125 focuses on a number of topics typical in an atoms-first presentation of first semester general chemistry but with an increased emphasis on structural considerations across chemistry. The primary goal of the course is to develop an understanding of chemical structures in inorganic and organic chemistry and biochemistry, so that students can begin to appreciate applications from diverse areas, including, for example, materials science, medicinal chemistry, and catalysis. Once these more pictorial ideas are in place, a more rigorous mathematical understanding of chemistry can be built.[24]

Figure 1 shows an overview of topics and the time devoted to each in a recent iteration of the revised course, Chem 125 (fall, 2014).[25] Sectors of the graph are color-coded based on the course in which each topic has been taught traditionally, and the sectors are arranged clockwise beginning at the top of the chart in the order in which the topics are covered. An alternative representation of the makeup of Chem 125 is presented in Table 1. Chem 125 is comprised of about one-third "traditional gen chem I", one-third "traditional gen chem II" and one-third "organic and biochemistry".

It is tempting to draw an analogy with a general and organic chemistry and biochemistry (GOB) course, typically aimed at nursing and health science students, but Chem 125 is deliberately more sophisticated. For example, a section on conformational analysis in hydrocarbons introduces students to the idea of simple basis sets in computational chemistry, and a section on bonding extends into a simplified treatment of Huckel molecular orbital theory in conjugated systems. Rather than looking solely at topics that might be useful in the health sciences, topics are chosen to appeal to majors in a variety of

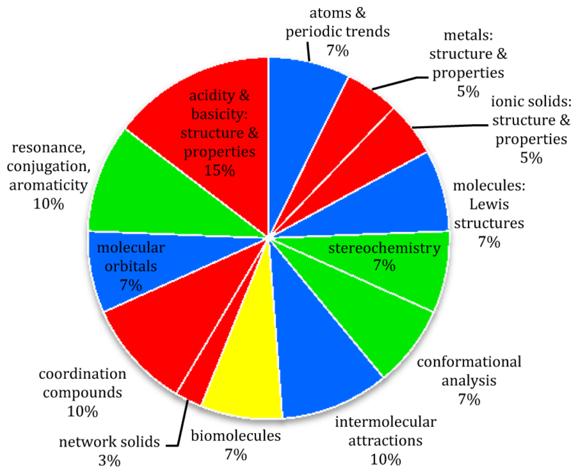


Figure 1. Percentage of class time spent on topics in Chem 125. Percentage is based on approximately 40 h of classroom time over the course of a semester. Colors correspond to the courses in which these topics have traditionally been covered at CSB/SJU (blue, General Chemistry I; red, General Chemistry II; green, Organic Chemistry I; yellow, Biochemistry).

Table 1. Class Time in Chem 125 on Topics from General and Organic Chemistry and Biochemistry

Course of Origin of Material	Instruction Time in Chem 125 (%)[a]
General Chemistry I	32
General Chemistry II	37
Organic Chemitry I	24
Biochemistry I	7

[a]Percentage is based on approximately 40 h of classroom time over the course of a semester.

fields, including chemistry, biology, geology, materials science, and environmental studies.

A fuller appreciation of course content can be gained by inspection of the online textbook;[37] a table of contents for this book has been reproduced in the Supporting Information.

Differences between Chem 125 and Traditional First Semester General Chemistry

Thinking in three dimensions is a major skill needed to understand structure.[26] This area has been identified as crucial for practicing scientists.[27] Practice in spatial reasoning is first introduced in the structures of metals and ionic solids, a topic typically reserved for second semester general chemistry at the earliest. In addition, concepts of stereochemistry and organic conformational analysis are developed here, although typically they would be delayed until a second year course. Further skills in this area are practiced by looking at the structures of network solids such as silicates and diamond; together with coordination chemistry, these are frequently "special topics" that might otherwise be introduced either in second semester general chemistry or an inorganic chemistry course. Biochemical structure is introduced first with carbohydrates, which follow logically from stereochemistry, followed by lipids and lipid aggregates, proteins, and nucleic acids, whose structures can be understood and appreciated through applications of intermolecular forces. Some introductory aspects of receptor theory are also addressed.

Acid and base chemistry in a conventional general chemistry sequence is typically covered in the second semester. Usually it is presented within the context of calculating concentrations in equilibria. The approach in Chem 125 is different, seeking to lay down principles of why particular compounds will act as proton donors and acceptors based on structure. In addition, students are introduced to the use of curved arrows as tools in electron bookkeeping. In other curricula, these approaches are more commonly addressed in organic chemistry. However, this application of structure−property relationships is widely understood as the basis for further studies in reactivity both in organic chemistry and beyond.[28]

In Chem 125, applications of chemistry are frequently emphasized, because introductory students need to know that the topic they are studying is relevant to their lives and society. For example, the discussion of three-dimensional structure in metals includes a look at austenite and martensite, two forms of steel that occur during metallurgy in the automobile industry, with attention to the physical properties of these two materials. A unit on ionic solids includes a short module on calcium-doped zirconium oxide as an oxygen sensor in cars. When studying stereochemistry, testosterone and epitestosterone are contrasted in terms of both absolute configuration and conformations; students also look at how these compounds can be assayed using gas chromatography−mass spectrometry (GC-MS) to determine whether an athlete has been doping. Intermolecular forces provide a plethora of applications, including the structure of paper, the remediation of oil spills, and receptor theory in biochemistry. Even molecular orbital theory, that most arcane of general chemistry topics, is extended so that students get a glimpse of band theory and its applications in semiconductors.

Thus, students in Chem 125 are exposed to a number of areas that are often ignored in the typical general chemistry curriculum. As a consequence, some topics must be left out. The elegant history of atomic theory is one casualty, for example. We have also chosen to leave out quantum numbers from the discussion of atomic orbitals, the origins of which are poorly addressed at the general chemistry level. However, we have preserved a qualitative approach to molecular orbital theory because it underlies so many discussions in inorganic and organic chemistry.[30] In addition, thermodynamics has been reserved for subsequent courses (Chem 250: Reactivity I, and Chem 255: Macroscopic Chemical Analysis). That decision also introduces limitations; for example, a discussion of solubility leaves out the important role of entropy in solvation.

One final difference concerns the role of quantitative aspects of chemistry in the introductory course. In general, we have scaled back the traditionally numerical flavor of general chemistry in Chem 125. Although the course does use mathematical arguments in developing some key concepts, more rote aspects of quantitative problem solving are minimized. It is vitally important for science students to be able to perform calculations and evaluate results, but these tasks are better appreciated once a student develops a picture of the system they are evaluating.[31]

This approach is best illustrated by considering how topics in our introductory course are further developed in subsequent ones. For example, equilibrium constants are conceptually introduced in the context of acid−base chemistry in Chem 125. Thermodynamic factors, including general concepts of enthalpy and entropy, are introduced within the context of other reversible reactions in the next course in the Structure and Reactivity sequence, Chem 250: Reactivity I. However, the rigorous calculation of free energy differences and concentrations in equilibria is reserved for Chem 255: Macroscopic

dx.doi.org/10.1021/ed400839y | J. Chem. Educ. 2015, 92, 237−246

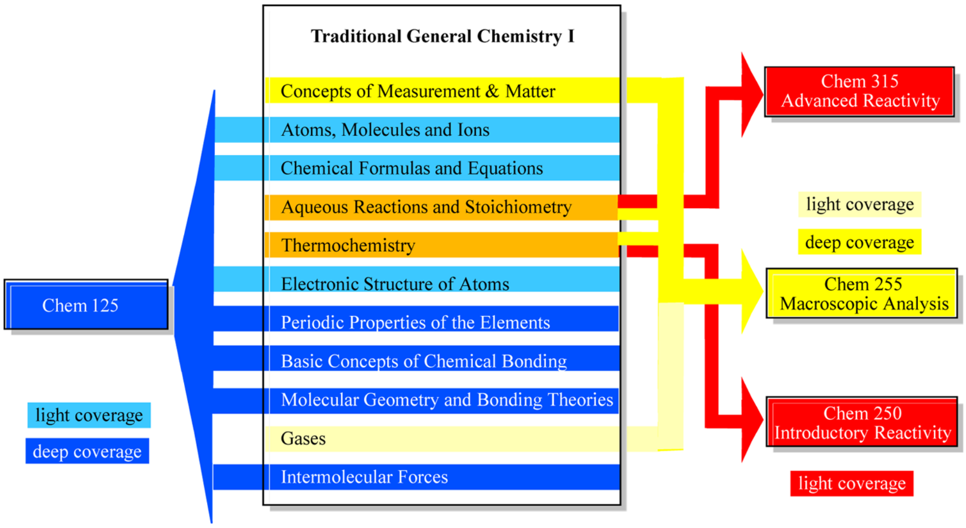


Figure 2. Topics traditionally covered in General Chemistry I[29] and their location in the CSB/SJU curriculum.

Chemical Analysis (Figure 2). Stoichiometry is also covered in Chem 255 as well as in other courses on an as-needed basis, such as in the calculation of yields in Chem 203: Synthesis Laboratory, or when balancing redox reactions in Chem 315: Reactivity III.

Chemical kinetics, another mainstay of general chemistry, is developed in Chem 251: Reactivity II, when students learn about nucleophilic aliphatic substitution reactions and ligand substitution. Once again, qualitative ideas about how concentration and time might alter the rate of reactions are first developed before proceeding through graphical and, finally, algebraic approaches.[32] Thus, the overall approach to algorithmic problem solving is to develop conceptual ideas before mathematical tools and to practice using these tools on an as-needed basis, rather than front-loading them into the beginning of the curriculum.

Overall, because of the curricular sequence in which it has been incorporated, Chem 125 as deployed at CSB/SJU is best understood in analogy to a "1−2−1" or "general-organic-organic-general/analytical" approach practiced at some colleges. Chem 125 would therefore be analogous to the first semester course in this sequence. However, there are differences. We do make explicit efforts in the subsequent two semesters to develop some ideas traditionally introduced in a traditional general chemistry course. Furthermore, those subsequent two semesters develop aspects of inorganic and biochemistry as well as organic chemistry.

■ PEDAGOGICAL APPROACH

We have employed a form of team-oriented guided inquiry in Chem 125.[33] Our typical class is comprised of 25 to 30 students, organized into teams of 3 to 4 students seated at a table together. Students are expected to do some reading and preparation before class, often enforced by online homework or "passports" due before class. Information is delivered in short (~10 min) lectures at the beginning of class, usually with a shorter (~5 min) recap at the middle of the period. These "microlectures" are interactive and may employ hand-held whiteboards to gauge student comprehension of the material; clickers, socrative, or other tools could also be used. Students spend the remainder of the period in groups working on exercises in a workbook.

The workbook employs a mixture of guided inquiry questions, to develop basic concepts, and problem-based learning scenarios, allowing the students to place the material in context. For example, a unit on ionic solids starts by asking some simple questions: what would happen to the size of an atom if an electron were added? What if an electron were taken away? If charges must balance in an ionic compound, what must be the formula for a given pair of ions? A series of exercises examines how ionic solids pack together, based on students' previous work with metals. Students eventually examine more applied problems, such as the structure and function of a zirconium oxide-based oxygen sensor in an automobile engine.

The immediate benefit of this approach, as demonstrated by others, is that students have the benefit of early feedback from both peers and an expert, even as they internalize concepts by working through the material. Classrooms are small, accommodating 25 to 30 students, and furnished with round tables, each seating 3−4 students, in order to facilitate cooperative work and discussion. In most cases, faculty assign teams based on common interests (e.g., team members are all chem majors or all premed) or performance (e.g., all team members are within the same 30% in class ranking, so that one student does not dominate). The course grade depends on a mixture of written homework, online drill assignments, and quizzes of various lengths, requiring frequent practice with the material.[34] Active participation is also part of the course grade, assessed through instructor observation as well as peer evaluation.

Instructional Resources

Custom publishing agreements have allowed us to provide students with background reading on the topics of Chem 125, selected from different textbooks that together cover the material we need.[35,36] Thus, a number of chapters from a general chemistry textbook are bound together with a few chapters from an organic chemistry textbook, providing one source of material in one place. These texts provided much-needed support for our students as they did background reading and practice problems. However, some students have reported dissatisfaction with this approach, either by verbal comments or in course evaluations. Specific comments include a dislike for the change in styles from one source text to another. Furthermore, because of the mix of chapters from

Table 2. DFW and Enrollment Data for Chem 125

	Chem 123		Chem 125			
	AYs 05–09[a,b]	AY 10[b,c]	AY 11[b]	AY 12[b]	AY 13[b]	AY 14[b]
Students	303	285	315	401[d]	405	392
ASO[e]	2.74	2.60	2.71	2.70	2.84	2.80
% W	6.7	10.5	6.3	8.7	7.4	5.1
% DFW[f]	12.5	16.5	10.8	11.0	9.2	9.5

[a]Traditional course. Reported numbers are the average over a 5 year period. [b]In each case, AY *n* refers to the calendar year of the spring semester; e.g., AY 13 denotes the 2012–2013 academic year. [c]Trial version with new course modules under old course number, Chem 123. [d]The addition of nearly 100 students to the course during AY 2012 to AY 2014 relative to the historical average (AYs 05–09) is related to curricular changes in the nursing and nutrition departments. [e]ASO is average student outcome, or average grade assigned, on a 4 point scale (*F* = 0; D = 1; CD = 1.5; C = 2; BC = 2.5; B = 3; AB = 3.5; A = 4). [f]DFW is the percentage of students receiving a grade of D or F or withdrawing from the course.

different sources in one place, students occasionally reported encountering 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 our students. On the other hand, the online homework content associated with these textbooks has been valuable, providing students with practice and rapid feedback. In the future, we are interested in exploring custom online homework packages that are not tied to the adoption of a specific textbook.

Because the unique collection of course topics does not afford a broad selection of commercially available resources from which we could choose, we have elected to produce our own workbook for class use. This guided inquiry-style workbook includes sections that gradually develop 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, push students to consolidate learning by placing new concepts in a variety of scenarios. The workbook is about 450 pages long, including occasional pages for extra note taking; see Supporting Information for availability.

In addition to a locally authored workbook, we have also developed a freely accessible supporting web text that presents information in an order similar to the classroom presentation of topics.[37] Some practice problems, with selected solutions, are also available at this site, and these aspects are continually being developed, improved and expanded upon.

Format

Chem 125 has been taught in three different formats and seems adaptable to different environments. Originally, it was taught during 70 min class periods in a rotating schedule: Monday, Wednesday, Friday 1 week and Tuesday, Thursday the next. Our institution has very recently transitioned to a fixed-week schedule typical of many colleges; Chem 125 is now being offered Monday, Wednesday, and Friday during 55 min periods. In addition, Chem 125 has been offered over a six week summer program with three 270 min classes per week. In each case, the total amount of instruction time is approximately 40 h; laboratory hours are counted separately. We have not encountered substantial problems when adapting the course from one format to another. Thus, we think the course can be adopted readily at colleges with a variety of schedules.

■ IMPACT ON STUDENTS

The introduction of material from more advanced courses into a first-semester course might be expected to overwhelm students, resulting in a noticeable drop in performance. An account of the percentage of students receiving a D, F, or W shows that, after an initial spike during a trial introduction period, these indicators have returned to normal range (Table 2). A temporary increase in grades of D, F, or W is not unexpected as a new curriculum is phased in.[3]

In addition, a curriculum change might result in adverse effects on the number of enrolled chemistry majors. The first semester course may be especially sensitive to these effects, as many students would reasonably form a first impression of the subject that will have a strong influence on their choice of major. The very different nature of Chem 125 compared to a more traditional general chemistry course, and especially compared to a high school chemistry course, could potentially leave students with a feeling of low self-efficacy that would result in decreased yield of chemistry majors.[38] In contrast, the number of chemistry majors graduating per year has not dropped; it may even have increased moderately since the introduction of Chem 125 (Figure 3). The magnitude of the effect is still unknown; 2013 graduates are the first cohort to have graduated after completion of Chem 125 (in a trial version), so this data is still preliminary.

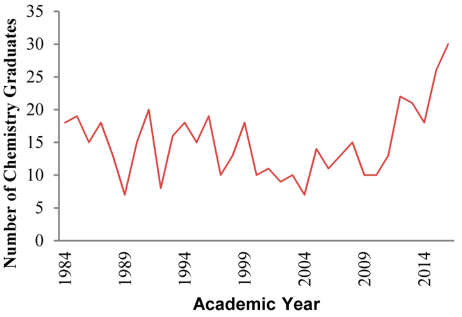


Figure 3. Number of chemistry graduates by year, 1984–2014 (and 2015–2016, projection based on current numbers of majors in upper division).

Less data are available concerning the impact of Chem 125 on nonmajors. Informal discussions suggest that many of the biology faculty feel Chem 125 serves their majors well. However, there is still some concern that a 1–2–1 format may not be good for all of the biology majors, since many students take only two semesters of chemistry and miss out on some quantitative aspects of the field.

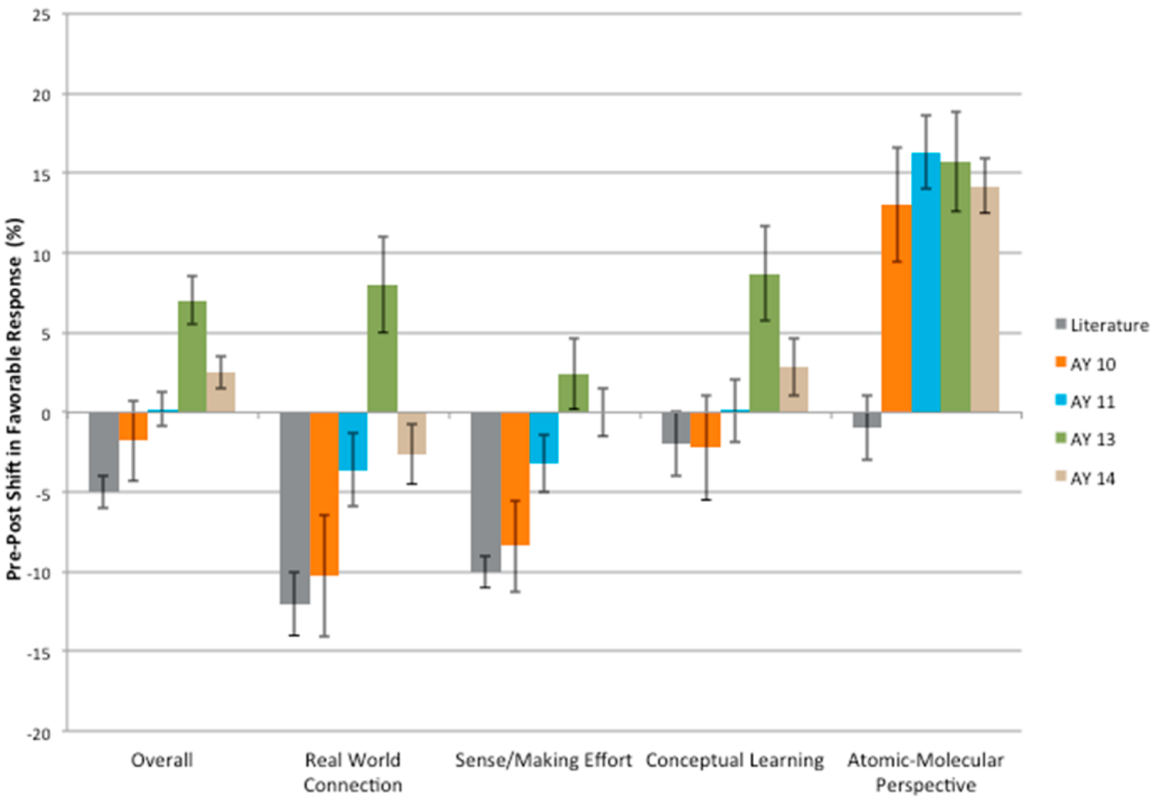


Figure 4. Selected results from Colorado Learning Attitudes about Science Survey.[39] Data shown are for fall semester (e.g., AY 10 means Academic Year 2010, or fall 2009−spring 2010, so the data are from fall 2009). Data was also collected in a small summer section; see Supporting Information. AY 10 introduced new modules into an existing General Chemistry I course; AY 11 and beyond were Chem 125.

Both nursing and nutrition/dietetics majors very recently began taking Chem 125 without a laboratory. Previously, nursing majors had taken no chemistry for several years, whereas nutrition/dietetics majors took a standard general/organic/biochemistry course with laboratory. A formal assessment of students' attitudes toward supporting courses for these majors is normally accomplished via a senior exit survey, but the nursing cohorts who took Chem 125 have not graduated yet. Informally, several students have commented positively to faculty about the pronounced problem-solving orientation of the class. Nutrition reports very little change from previous years.

Assessment

A Colorado Learning Attitudes about Science Survey (CLASS) was administered to assess students' level of confidence in specific areas before and after a course (Figure 4 and Supporting Information).[39] This survey, consisting of about 50 questions, was first given to CSB/SJU chemistry classes in fall 2009. At that time, we introduced several planned modules for our new course within the context of our old, first-semester general chemistry class. The course was implemented in its present form during fall 2010 but has been modified each year. Because of concerns that our students were taking too many surveys, the CLASS was not administered during fall 2011 but was resumed in fall 2012. An option of taking Chem 125 in the spring semester was introduced in 2012, mostly in response to increasing enrollments from nursing, nutrition, and dietetics majors who began taking the course that year, but CLASS has not been administered in the spring semester. Student responses were voluntary and the response rate over this multiyear period was approximately 50%, but fluctuated from year to year.[40]

It is reported in the literature that there is typically an overall decrease in confidence across all categories in the first semester of general chemistry. We observed a similar trend, with the exception that students reported significant gains in their understanding of atomic and molecular perspective. This result appears to be strong validation of efforts to implement spatial reasoning skills and develop a stronger understanding of structure and bonding throughout the course.

In other areas, most notably in making a real world connection to chemistry, students reported a smaller loss of confidence than that reported in the literature. In addition, a positive shift in outcomes is apparent between fall 2009 and fall 2013. This improvement may have resulted from modifications instituted in the course over that period.

Each category of question in CLASS is comprised of between four and ten individual questions. In some cases, an overall shift in a category of questions may reflect a mix of favorable and unfavorable shifts for individual questions. Representative data on responses to some of the individual questions are provided in the Supporting Information.

It should be noted that lower survey response rates in both 2009 and 2012 may contribute added noise in the data (see Supporting Information). Furthermore, the exceptional results from the fall 2012 class mirror impressions from instructors in subsequent courses, ranging from organic chemistry to quantum chemistry, who felt this group produced a class of very strong majors. Although a number of sections of Chem 125 are taught at CSB/SJU each year, they are generally taught

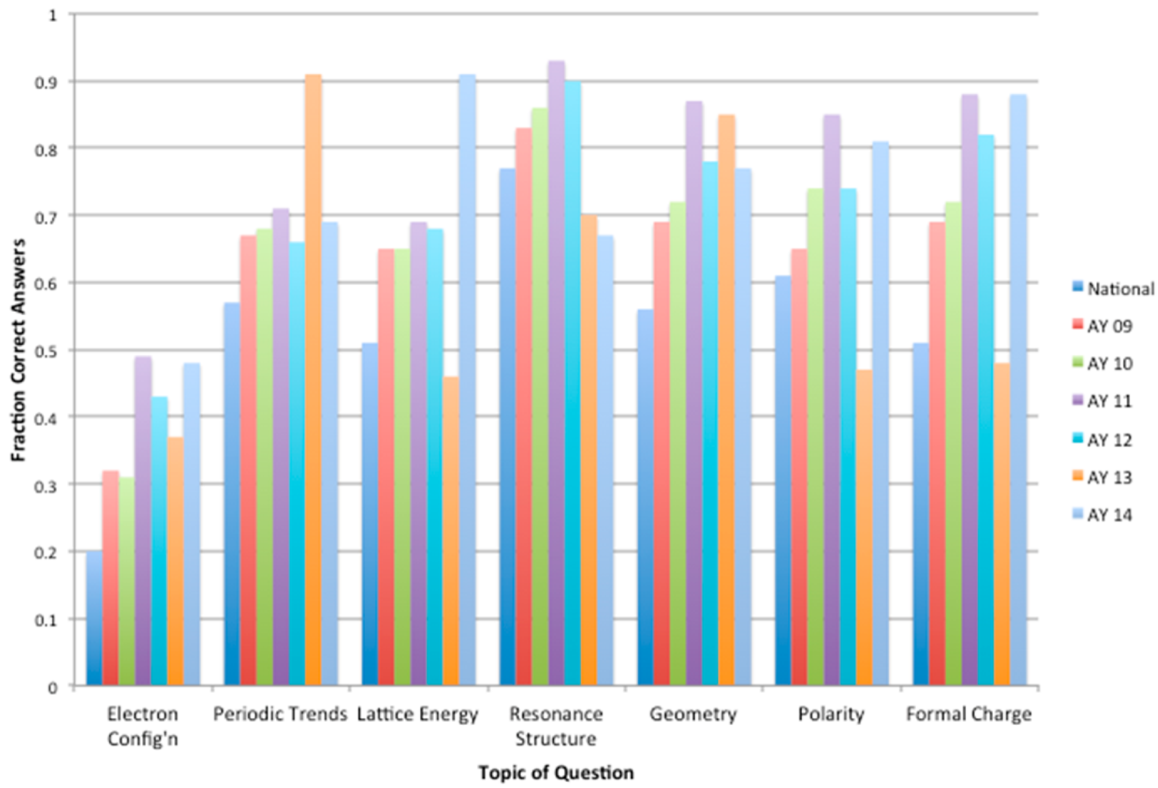


Figure 5. Results from selected questions from ACS general chemistry exam: GC A, electronic configuration; GC B, periodic trends; GC C, lattice energy; GC D, resonance structure; GC E, hybrid geometry; GC F, bond polarities; GC G, formal charge. AY 09 (Academic Year 2009, or Fall 2008−Spring 2009) was a traditional general chemistry course; AY 10 introduced new modules into an existing General Chemistry I course; AY 11 and beyond were Chem 125. Total course enrollments: AY 09, 322 students; AY 10, 285 students; AY 11, 315 students; AY 12, 401 students; AY 13, 405 students; AY 14, 392 students.

by the same group of instructors, so yearly variations in responses are probably not strongly linked to instructors.

Because of the hybrid nature of Chem 125, the use of standardized testing to assess student progress has been problematic. We have had students take a final exam that included questions from different ACS exams in general and organic chemistry in an effort to match course content with assessment tools. This task was undertaken with cooperation from representatives of the ACS Exams Institute. However, interpretation of the results is complicated by the fact that our students encounter these questions under circumstances different than students nationally. Nevertheless, we believe this information has been helpful to us in illuminating some of our strengths and weaknesses.

Previously, we had instituted a first semester ACS exam in general chemistry (Chem 123), so we have been able to compare some of those results (AY 09) to results for the same questions encountered by Chem 125 students (AY 11−14). In each case, we compared the fraction of students getting the correct answer on an identical question (Figure 5). Our objective was to determine whether the students who took Chem 125 performed significantly better on ACS exam items than the students who took the traditional general chemistry course. We also wanted to investigate whether the Chem 125 students outperformed the national pool. The Student's t test (two-tailed) was used to test for significant differences between the data. Formally, we performed two statistical tests and evaluated the results at 95% confidence interval ($p \leq 0.05$). For the first test the null hypothesis was that the difficulty index score of Chem 125 students on ACS items was equal to that of students who took the traditional general chemistry course. Statistical analysis showed that Chem 125 students performed significantly better on two ACS exam items (electronic configuration and hybrid geometry) compared to traditional general chemistry students. There was no statistically significant difference between the two student groups for the five other items that were assessed, indicating a similar level of performance. For the second test the null hypothesis was that the difficulty index score of Chem 125 students on ACS items was equal to that of the national pool. Statistically significant difference was observed for three ACS items: electronic configuration, periodic trends, and hybrid geometry. We assume that the significant gain in understanding of electronic configuration and hybridization/geometry is bolstered by the ongoing work with Lewis structures in the more "traditionally organic" aspects of the course.

We did not previously employ a first semester organic chemistry exam, so we do not have good before and after data for the organic topics. We have instead compared results from AY 11−14 to data from the ACS national pool on those topics (Figure6). Student's t test (two-tailed) was performed to test the null hypothesis that the difficulty index score of Chem 125 students on ACS items was equal to that of the national pool. Statistical analysis showed that Chem 125 students' difficulty score was significantly higher for one ACS item (acyclic conformational analysis) and similar to the national pool for all other items assessed. Overall, our first semester students fared comparatively even with fourth semester students elsewhere on these introductory organic chemistry topics.

dx.doi.org/10.1021/ed400839y | J. Chem. Educ. 2015, 92, 237−246

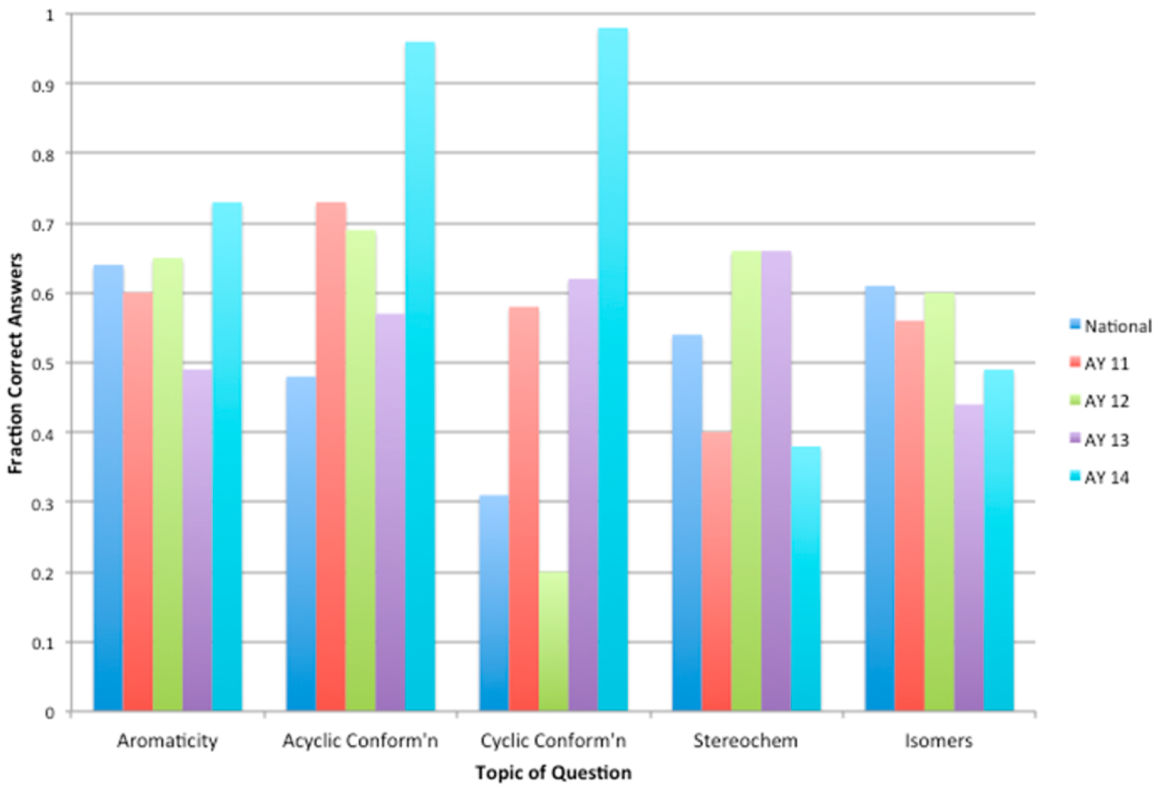


Figure 6. Results from selected questions from ACS organic chemistry exam: OC A, aromaticity; OC B, acyclic conformational analysis; OC C, chair conformations; OC D, stereochemistry; OC E, types of isomers. Semesters shown are Chem 125 only. AY 11 is Academic Year 2011, or fall 2010–spring 2011.

Students fared noticeably worse on a cyclic conformation question during fall 2011 (AY 12, Figure 6) and on a number of topics during fall 2012 (AY 13, Figure 6). We do not have an obvious explanation for that problem. Year-to-year differences could reflect personnel changes (two new adjunct instructors were teaching the course during AY 12, for example). There may be random variation in student ability or motivation. It is also possible that a topic that proved difficult for students one year was emphasized more strongly the next, but at the expense of another topic. For example, students in AY 2013 did well on periodic trends but poorly on formal charge, polarity, and lattice energy; the opposite was true the following year.

■ CONCLUSION

We have instituted a new first semester college chemistry course that takes an atoms-first approach further by continuing a natural narrative into metallic and ionic solids, organic molecules and biomolecules, and coordination compounds. We have seen substantial improvement in students' confidence in the area of molecular structure and properties. Overall, Chem 125: Structure and Properties appears to be a promising springboard for our chemistry curriculum.

At CSB/SJU, this new course has been implemented in the context of an overall curriculum that is reminiscent of a 1–2–1 approach, with an introductory "general chemistry" course immediately followed by an "organic chemistry" course. It is conceivable that this course could be employed in a more typical two semester sequence of general chemistry, provided appropriate modifications were made to the second course. However, some of the advantages of preparing students in the area of molecular structure and properties might then be lost over time, and those topics are crucial in organic chemistry.

Instructors who do choose to implement this course in a more traditional setting will find that it provides students with a challenging introduction to chemistry. Because course topics deviate somewhat from those already covered in high school, Structure and Properties provides a level playing field in which all students quickly encounter stimulating new material. Subsequent courses would require minor modification. For example, structural topics of conformation and stereochemistry would be moved out of organic chemistry, providing more time for other topics.

The pedagogical approaches described herein have made it easier to transition to a new course. The use of guided inquiry workbooks helped keep instructors in different sections to provide more uniform instruction on unfamiliar terrain. Nevertheless, an instructor with ample experience teaching the range of topics in Structure and Properties could presumably develop a lecture-based course, even with a large number of students. Alternatively, a large section might employ teaching assistants to interact with students as they go through workbook exercises in the classroom.

We are continuing to develop additional courses that break down traditional barriers between subdisciplines of chemistry and present common aspects of organic, inorganic and biochemistry. These new courses are being assessed through a combination of student opinion surveys and performance on ACS exam questions. We will report on these developments as they are implemented.

In closing, we encourage other departments to embark on their own programs of curricular revision, however minor or radical. Although the amount of work involved has been significant in the case described here, the endeavor has been invigorating. The revisions to the ACS curricular guidelines were clearly designed with innovation in mind, paving the way for a true renaissance in chemistry teaching. Ultimately, independent revisions of the chemistry curriculum may prove to be the best laboratory for developing new and effective approaches to instruction.

■ ASSOCIATED CONTENT

Supporting Information

Sample course syllabus, course description, daily class schedule, additional assessment data, sample workbook pages, table of contents of online textbook, and information on ordering a sample Chem 125 workbook from Academic Pub and other resources. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We acknowledge helpful discussions with Carie Braun and Jane Byrne of CSB/SJU and Tom Holme of Iowa State University. We also appreciate Carleen Schomer's willingness to adapt to Chem 125 even after her formal retirement.

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(40) An exemption was obtained from the CSB/SJU institutional review board as part of a grant application to the National Science Foundation.