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Designing convergent [chemistry] curricula

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Scientific convergence is a common theme of modern research, but undergraduate chemistry is commonly taught as an isolated discipline. Here we discuss curricular updates at three different institutions which are independently seeking to increase convergence in introductory chemistry courses.

In the United States and Canada, most introductory chemistry curricula consist of a full year of general chemistry followed by a full year of organic chemistry. These courses teach not only future chemists and chemical biologists, but also future professionals in related fields including medicine and engineering. These students are already taking introductory courses in biology and other disciplines, and most are motivated not by the knowledge itself but the desire to solve cross-disciplinary problems such as sustainable energy and disease. However, the typical introductory course teaches chemical principles in a manner that is disconnected from other disciplines and detached from modern experimental research. This type of introductory curriculum is like a tunnel, in that students are taught abstract molecular concepts but most cannot see immediate relevance to their scientific passions. Instead, students must blindly trust that the material will be useful once they get to the other end. This “tunnel” can drive away students who are otherwise enthusiastic about molecular science, and it may not be optimal even for students who are preparing for research careers in chemistry and chemical biology. For all these reasons, we contend that scientific convergence (the growing connectedness of once-disparate scientific disciplines)[1] should be reflected in modern science education - not just in upper-level and enrichment courses, but in introductory chemistry as well.

Chemical biology has been a defining example of a convergent discipline that is more than simply the intersection of chemistry and biology. Similarly, other areas of research have been steadily converging, because solving the big problems of our age requires cross-disciplinary expertise.[1–4] Professional guidelines for chemistry as a whole have shifted, in part to recognize the growing importance of convergent fields such as chemical biology. In 2008 the American Chemical Society (ACS) made a major revision to its *Guidelines and Evaluation Procedures for Bachelor’s Degree Programs*, explicitly pushing for curricular flexibility that reflects the breadth of modern science; flexibility has been emphasized further in more recent revisions and clarifications.[5–8] Guidelines for pre-medical students have also changed. The American Academy of Medical Colleges (AAMC) has replaced its curriculum with core competencies, and the new MCAT focuses on cross-disciplinary knowledge and applications.[9,10] The American Society for Biochemistry and Molecular Biology (ASBMB) has responded to the new MCAT by suggesting specific curricular reforms, including making introductory chemistry more relevant to students interested in life science.[11,12] Making curricula more convergent addresses a natural overlap between the training required by 21st-century health professionals, and the training required by 21st-century research scientists. Taken together, these recommendations should be sparking a reconsideration of the “tunnel” of introductory chemistry courses, but so far few schools have implemented significant changes.

There are a handful of innovative curricula that try to shorten or eliminate the introductory tunnel (Table 1). “Organic first” curricula have been developed by Juniata College and University of Michigan, and biology-focused introductory chemistry sequences are offered at several universities including Harvard and Purdue.[13–16] At most institutions, however, curricular change has been slow or nonexistent. In 2014, a National Academy of Science (NAS) report summarizing a workshop on Undergraduate Chemical Education urged educators to drop the “formalism first” approach in favor of a more interconnected view of molecular science.[17] They noted that there are many barriers to implementing more convergent curricula. These include buy-in from faculty, coordination with other departments, availability of appropriate textbooks and teaching materials, ability to accommodate transfers from other 4-year and 2-year colleges, and the need for funding to implement changes and assess their impact. As we illustrate below, these barriers can be overcome by staging open and self-reflective discussions with chemistry faculty and with faculty from related disciplines, by designing optimal curricula rather than simply selecting a textbook and following it linearly, and by coordinating with administration and with chemistry departments at other institutions.

There are many ways to address the above recommendations, but we contend that the optimal change is to reorganize multi-year introductory chemistry curricula into three-semester molecular science courses. These courses should focus on chemistry concepts that span disciplines, and they should apply these concepts to all areas of science, engineering, and medicine. After all, concepts of molecular structure, reactivity, thermodynamics, kinetics, and quantitative analysis can be taught in the context of nearly any chemical system, but these topics are often introduced using examples that are exquisitely specific to chemistry. Sometimes, faculty lament that students subsequently cannot apply these concepts in upper-level courses. We suggest that, when taught using broad examples from different disciplines, these concepts can be instilled as general principles of any molecular system, and will be more readily applied by the student to more complex systems.

In our own departments, we have sought to implement curricular changes that: 1) maintain enough depth and rigor to prepare chemistry majors for upper-level classes, 2) broaden the scope to better serve students interested in life science and engineering, and 3) use this depth and breadth to demonstrate the nature of real research problems. Below, we describe three independent approaches toward the eventual goal of a fully convergent curriculum. These changes were faculty-initiated and tailored to each department's needs and vision. By sharing these experiences, we aim to demonstrate that it is possible to begin this transition *now*, and that curricular change can be implemented at a scale and pace appropriate for different institutions.

Organic Chemistry at Tufts University

At Tufts University, our General Chemistry and Organic Chemistry courses were geared towards relevance for chemistry and biochemistry majors, even though these individuals make up a minority of students in these classes. While the ACS and AAMC guidelines were not the driving force behind making curricular changes, they did help muster support for holding wide-ranging faculty discussions to re-evaluate introductory courses. In discussions within the chemistry department and across the university, we recognized that carbon-based chemistry is of broadest interest, and that all students need at least some understanding of the chemistry of life. Thus, key topics taught in general chemistry and organic chemistry were considered as independent units and re-grouped, in order to move topics of broader interest as early in the curriculum as possible.

Ultimately, we rearranged and consolidated topics in organic chemistry, and made smaller adjustments to general chemistry and biochemistry curricula. The two semesters of general chemistry use applications from all areas of molecular science, and we produced a transitional unit that broadly introduces students to organic molecules. This ensures that, after one year of chemistry study, students are already familiar with carbon-based functional groups found in nature and key concepts like resonance, chirality, and conformational analysis. The two-semester organic chemistry sequence underwent a more major reorganization. The explicit goals were to minimize reaction memorization, instead focusing on fewer reactions that nonetheless illustrate key reaction types and reactivity concepts. The first semester uses this extra focus to spend time on alcohols, ketones, carboxylic acids and enolates, in order to inform core biochemical mechanisms. Topics that are rarer in biology, such as alkynes, organic radicals, and organometallics, are saved for the second semester where their usefulness for organic synthesis can be the primary focus. This allows a single semester of organic chemistry to serve as a prerequisite for a graduate-level, mechanistic biochemistry course, which students can now take in the spring of their second year.

These changes were implemented in 2013 and are revisited every year by the organic faculty, in consultation with the entire chemistry faculty and other science departments. No additional resources were required to implement these changes, since they required only faculty buy-in and no new technological or pedagogical tools. For texts and study materials, we designed our optimal curriculum first, then chose existing materials that allowed us to execute the curriculum. We use a general chemistry textbook with an ample introduction to carbon-based chemistry, and an organic textbook that is modular enough to allow us to study chapters and sub-chapters in a customized order without significant problems. Thus, we have implemented changes using existing, tried-and-true study materials.

The effects on students interested in life sciences have been profound. Being able to take Biochemistry prior to upper-level biology courses has exponentially improved their understanding of biology, and has begun to erase the artificial divide between introductory chemistry and introductory molecular biology. After an initial adjustment period, students focused on physical science and engineering are receiving a similar overall curriculum as before, but topics are introduced in a different order and in a broader context. Courses were reformed without dedicated funding, but there is a ceiling for no-cost improvements. We anticipate requiring funding for quantitative evaluations and for overhauling lab courses. As these funds become available, we will be able to expand our efforts to make introductory chemistry even more immediately relevant and even more solid a foundation for a variety of careers.

Molecular Science at Stony Brook University

At Stony Brook University, we were prompted to develop an integrated Molecular Science course sequence after noticing that, despite offering honors, regular and developmental tracks, each course would have students with a wide range of prior preparation. Invariably, some students were merely repeating what they had already learned in high school, while others were struggling. We recognized that students' self-selection of introductory chemistry courses could be replaced by mandatory placement based on direct assessment of student preparation. Moreover, a preparation process that ensures students share a common platform of knowledge and would free up instructional time to allow greater focus on what are traditionally considered advanced topics. Ultimately, this process provided the freedom to develop a new introductory course sequence that recognizes the changing nature of science. This sequence, Molecular Sciences I, II and III, covers the material found in the conventional two-year introductory sequence by connecting and integrating topics, including concepts from materials science and the life sciences. This process has resulted in better-matched cohorts of students in individual classes, more freedom to connect chemistry to biology and other disciplines, and better student outcomes.

In order to accurately pre-assess student knowledge and assist in individualized preparation for college chemistry, we applied the assessment and learning tool ALEKS, which relies on knowledge space theory.[18] Our online process places students in courses, sets clear expectations for students as they progress, and most importantly, prepares and assists students to meet the course's learning objectives. This process ensures each course enrolls students with similar chemistry and math backgrounds, allowing faculty to focus on chemistry that is new and exciting and keeping that chemistry relevant to students' interests and future careers.

The online system better prepares all students for college-level chemistry, and most still enroll in a "traditional" four-semester sequence. The best-prepared cohort is placed into the three-semester Molecular Sciences sequence. The first semester of Molecular Sciences introduces key concepts such as quantum theory, thermodynamics, quantitative equilibrium, and kinetics, but in the context of important topics in organic chemistry. In the second semester, students explore structural, mechanistic and synthetic aspects of organic chemistry, but in the context of important problems in catalysis, supramolecular chemistry, and polymer science. In the third semester, we discuss more advanced structures, mechanisms, and synthetic strategies, tying them directly to key concepts in biology and biochemistry. The lecture and lab sequences were revised to be tightly coupled, providing hands-on applications of course content. Developing the Molecular Sciences sequence has also spurred changes in the four-semester sequence. In both sequences, students now focus less on memorizing reactions and more on solving problems using important chemical concepts. Both curricula are designed to give students a more sophisticated view of chemistry from the beginning of their college studies.

The Chemistry Department at Stony Brook University has a long history of curriculum development through data analysis, with continuous revision based on student needs and demographics. The Molecular Sciences sequence was implemented through much faculty discussion, and required a redistribution of resources. Shortening the foundational sequence to three semesters freed up resources for the online placement process, and other costs are incorporated into existing course fees. The Molecular Sciences sequence will sustainably evolve to meet future needs. We continue to teach a four-semester sequence for those students with less preparation but, based on the implementation of the Molecular Sciences sequence, we will address integration of the four-semester sequence in the future.

Themed Courses at Haverford College

We were motivated to change our curriculum at Haverford College in order to ensure our students receive a rigorous and modern chemistry education that fosters habits of scientific inquiry. We realized that our introductory courses could be reorganized into themes which integrate topics from different disciplines while acting as springboards into more advanced chemistry material. The possibility of revising our introductory curriculum was an ongoing item on our departmental meeting agendas for a few semesters, which provided faculty time to brainstorm possible modes of implementation. We then held several departmental retreats to work through details, and ultimately decided to reorganize our introductory sequence into four courses: Chemical Structure and Bonding, Chemical Dynamics, Organic Biological Chemistry, and Organic Reactions and Synthesis. In our previous curriculum, our general and organic chemistry courses followed a traditional format, in which the discussion of carbon-containing molecules and spectroscopy were deferred to organic chemistry. We revised our approach such that students are exposed to the chemistry, structure, and spectroscopic characterization of all molecules, including organic molecules, in their first semester of college chemistry. We now actively integrate these themes throughout the lecture and laboratory components of all four introductory courses. In their first year, students are introduced to the theories of chemical bonding that rationalize and predict the structures and bulk properties of molecules and materials (semester 1), and the fundamentals of reactions from a stochastic point of view (semester 2). Since our first-year sequence integrates discussion of carbon-based molecules with the rest of the periodic table, students already have experience with chirality, aromaticity, and spectroscopy, and can already discuss exciting applications in chemical biology. In their second year, students are exposed to a panoramic view of organic mechanisms relevant to biological systems in the fall. Notably, we now dive straight into carbonyl chemistry and sophisticated spectroscopy (such as 2D NMR) in the fall of the second year, while the spring focuses on concepts relevant to synthetic organic chemistry, such as competition between elimination and substitution reactions, retro-synthetic analysis, and reaction mechanisms in non-aqueous solvents. At all levels, we provide inquiry-based experiments in the laboratory portion of the class, including challenging our students to design and execute a multi-step synthesis by the end of their second year. Our approach provides an earlier branching-off point for non-chemistry majors because the first three semesters fulfill all pre-health requirements. Our curriculum also provides multiple entry points, including an advanced laboratory for first-years with extensive chemistry backgrounds, an intensive section that meets five-days-a-week for freshmen with weaker preparation, and a one-semester chemistry option (Chemical Dynamics) for environmental studies minors.

We recognize that, as a nimble department with eight tenure-track faculty, we were able to progress from brainstorming to implementation more rapidly than many other institutions with a larger faculty. Still, our rapid transition has allowed for extended qualitative assessment of our objectives. Teaching around themes has allowed us to tackle advanced material in an integrated manner, so chemistry majors and non-chemistry majors all learn useful knowledge and problem-solving skills. Student-led inquiry is emphasized in both the lecture and lab components of these courses. Anecdotally, we have observed increased comprehension of core chemistry concepts, along with greater excitement over an introduction to molecular sciences that students appreciate as sophisticated, modern and relevant. More tangibly, we have observed a growth in the number of students majoring in chemistry, with a notable increase in majors coming from cultural and socioeconomic backgrounds that are traditionally underrepresented in the sciences. This positive experience has generated further support for continual revision of our courses, keeping pace with student needs and the convergent nature of modern research.

Boarding up the tunnel

Similar barriers to curricular change exist everywhere: faculty inertia must be reversed, changes must be coordinated among faculty from chemistry and other science departments, appropriate texts and study materials must be identified, and funding must be secured. These barriers can be overcome, and doing so can revitalize introductory curricula that have largely stagnated for decades. Our experiences demonstrate that there is no one model for specific changes. Tufts chose to begin reforms with Organic Chemistry, Stony Brook began by producing a new introductory sequence for their best-prepared students, and Haverford made wholesale changes to their entire introductory curriculum for all students. We do not prescribe any single model, but rather stress that curriculum reform can happen in many different ways, with similarly positive outcomes. Discussed below and summarized in Box 1 are some common features among our experiences that may provide starting points for other institutions to implement similar changes:

- *New curricula were designed with professional standards in mind*. All of our departments were motivated to respond to changing standards of professional societies and graduate programs. However, we did not hew slavishly to any one set of recommendations. We focused on achieving learning objectives, rather than developing one rigid curriculum to replace the last. Our departments carefully considered the volume of our students, their levels of preparedness, and the teaching loads of our faculty, and made changes that served these specific needs.
- *New curricula were implemented independently from new teaching strategies*. Many institutions, including our own, are implementing new teaching strategies. These changes are driven by evidence that active learning increases student engagement and comprehension.[19,20] The question of *what we are teaching* in introductory courses is just as important as *how we teach*, but has received less critical examination. We advocate that changes in introductory curricula should be implemented independently from changes in teaching strategy. While both can be developed simultaneously, it is important to consider separately their planning, implementation, and evaluation.
- *New curricula provide a three-semester introductory sequence.* This shorter sequence prepares students for advanced coursework such as biomedical engineering, physical chemistry, inorganic chemistry, biochemistry, and chemical biology before the end of their second year of study. Chemistry and Biochemistry majors still take advanced courses in most or all of these topics, but non-majors can "branch

off" and specialize in other, related fields after only three semesters. In our experience, chemistry and biology faculty teaching upper-level courses have welcomed the students' ability to take on specialized material at an earlier stage. And, for those students preparing for medical school, the reframed course sequences allows them to be better prepared to take the revised MCAT exam by the end of their junior year.

- *The focus was shifted from memorizing details to mastering threshold concepts.*[21,22] Since the courses are more concise, some content must be categorized as too specialized for introductory courses and postponed to upper-level courses. Perhaps in the near future a new consensus will emerge, but with choices about content and pacing left to individual institutions and departments, the topics that are shifted may vary greatly. Thus, it is essential to engage faculty from other science departments in conversations about the most important prerequisite chemistry learning outcomes for their courses. For instance, coordination with the Biology Department at Tufts prevented omissions of any material or skills deemed necessary for Molecular Biology courses and labs. As long as key material and concepts are included, we have observed that focusing on core concepts provides a firmer foundation for more advanced coursework across many disciplines.
- *Implementation was low-cost or no-cost.* While there are some initiatives that aim to completely overhaul undergraduate science curricula, change does need not be grand in scope or especially well-funded to have large effects. Our examples and others demonstrate that curricular change can be implemented incrementally using moderate resources, at a scale and speed that matches overall departmental goals. Lecture courses were surprisingly easy to reform, because once a new curriculum was agreed upon, existing materials could be adapted to teach it. This was accomplished either by proceeding nonlinearly through a text that was comprehensive but modular, or by using custom-written problems and materials and using textbooks more as references. While textbooks catering to new course structures will undoubtedly be produced, perhaps more flexible texts with modular chapters (such as *Chemistry*[3], used by Stony Brook for their Molecular Sciences courses) will provide the greatest support to new chemistry curricula.
- *New courses avoided creating parallel tracks for chemistry majors and non-majors.* Parallel course sequences limit interactions among students with different career paths, and can unnecessarily pigeonhole students who want to explore multiple career options. It also dangerously reinforces the wider notion that science must be modified or "watered-down" for non-scientists.
- *New curricula reflect the convergence of modern research*, particularly the convergence of chemistry and biology. By erasing hard boundaries between disciplines, the usefulness and applicability of core concepts became more obvious to students. This, in turn, reinforced the importance of being able to understand and apply these concepts to simpler, chemistry-based problems.

Growing support for "boarding up the tunnel"

All of the recommendations listed above make introductory sequences more self-evidently useful to students, thus eliminating the "tunnel" aspect to introductory chemistry. Our reforms and experiences are representative but not unique. Other departments are likewise in transition, taking their own paths towards more convergent curricula.[23–25] To monitor these transitions in real time, we have produced a web-based resource that will compile details of curricular changes in college-level general chemistry and organic chemistry sequences. At http://sites.tufts.edu/ConvergentChemistry, you can view curricular innovations from a large variety of colleges and universities (see Table 1 for a condensed version of this data set). We encourage new submissions, and the site will be continuously curated with additions and updates.

By providing and maintaining this resource, we hope to reduce barriers to change in several ways. First, it will raise the visibility of convergent curricula, beginning the discussion in some departments and accelerating change in others. Second, by demonstrating a critical mass of movement in this direction, we can persuade skeptical administrators and publishers to support these initiatives with funding and new teaching materials. Third, it will allow new standards to emerge, simplifying coordination among 2-year and 4-year colleges – until then, supplementary classes and materials must be provided to avoid roadblocks for transfer students. We are highlighting common themes, such as the movement towards a three-semester introductory sequence, in order to encourage others to reform along these lines, but we argue that a new monolithic curriculum should not arise to replace the old one. Instead, these common themes should be used as starting points for institutions to develop their own convergent curricula. Finally, we hope to spur investment into quantitative assessment of new curricula, similar to the recent focus on quantitative assessment of teaching methods.[19,20] While this will be harder than assessing changes to a single course, funds for evaluating the effects on student outcomes are critical if we are to fulfill our goals of preparing students for 21st-century medicine, engineering, and research.

Introductory chemistry should not be a journey through a dark tunnel, and students should not be told that they can only satisfy their real-world curiosity once they emerge from the other end. Instead, the journey's purpose should be readily apparent from every point along the way.

- ***Keep professional standards in mind.*** All of our departments were motivated to respond to new recommendations by ACS, AAMC, ASBMB, NAS, and others.
- ***Implement changes independently from new teaching strategies.*** We should take a fresh, independent look at the content itself in introductory chemistry courses.
- ***Provide a three-semester introductory sequence.*** A three-semester sequence can effectively prepare all students for upper-level coursework in a variety of fields.
- ***Shift the focus from memorizing details to mastering key concepts.*** Instead of teaching a toolbox, teach general tools for understanding molecular behavior.
- ***Implementation is not expensive.*** Curricular change can be implemented incrementally using moderate resources, especially for lecture courses.
- ***Curricula should reflect the convergence of modern research***. Discuss all types of molecules when introducing key concepts, so it is clear they apply across disciplines.

Table 1. Brief summary of institutions that have updated introductory chemistry curricula. Complete details are available at http://sites.tufts.edu/convergentchemistry/list/

Institution	Intended audience	Major change
College of St. Benedict / St. John's University	All students	Organized based on principles of structure, reactivity, and quantitation.[23]
Furman University	All students	Three-semester sequence, with a fourth semester dedicated to bio-organic chemistry.[24]
Haverford College	All students	Organized based on themes
Oberlin College	All students	Variety of tailored first-year introductory courses, second course in organic sequence can be bio-organic chemistry, organic synthesis, or both
Purdue University	Non-chemistry majors concentrating on careers in health care	Focused tightly on information relevant for biological sciences
Ripon College	All students	Organic Chemistry I is taught first, followed by a more general introductory course called Structure and Reactivity
St. Olaf College	Students with a strong interest in the	Integrated chemistry/biology first-year sequence[25]

	chemistry-biology interface	
Stony Brook University	Advanced students	Integrated concepts from throughout chemistry into one three-semester sequence
Tufts University	All students	Refocused on key topics and accelerated entry into mechanistic biochemistry
University of Michigan	All students	Organic chemistry taught first, followed by classes on physical principles and quantitative analysis[16]
University of Minnesota, Rochester	Health sciences majors	Organic chemistry taught first, with an emphasis on structure/reactivity principles
University of Richmond	All students	1-2-1 curriculum (one semester of introductory chemistry, two of organic, and one of inorganic)
University of Wisconsin, River Falls	All Chemistry and Biology majors and minors	Organic chemistry taught first, as part of a three-semester sequence

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