Teaching and Learning Assessment in Chemistry

The chemistry major provides the chemical principles underlying more macroscopic phenomena. Chemistry serves as a bridge between physics, biology, medicine, engineering, material science, nanoscience, and medicine. As a consequence, the chemistry department services the largest population of students of any science at Cornell. The major has a number of requirements, including a total of 60 credits of chemistry and related subjects.

I. Theme:

The chemical world can be described in terms of a small number of recurring chemical principles with very broad impact and application. They can be represented both descriptively in highly structural terms and mathematically. The interfacial role that chemistry plays will dominate the complexion of the chemistry major going forward.

Chemistry majors are expected to graduate with an understanding of a substantial portion of the core concepts, findings, and methods in contemporary chemistry, and with an ability to read and understand primary research papers. They are also expected to design experiments to test chemical principles; (2) critically analyze data; and (3) understand the dominant analytical and computational methods used to examine structure and reactivity. Majors are also expected to have some proficiency in oral and written expression to discuss and debate contemporary chemical issues. Chemistry majors should graduate with a clear understanding that valid theses are empirically testable and understand the appropriate tools to do so.

This report summarizes the department's learning goals and objectives and its strategies for assessing learning outcomes. The goals are achieved using two tiers of freshman- and sophomore-level lecture courses that converge into a single junior level sequence. A single sequence of laboratory courses span the sophomore and junior year. The assessment of the major described herein follows a departmental reevaluation and overhaul of the chemistry major to address the future needs of chemistry. The overarching theme is founded on our experience with a non-certified "alternative" chemistry major designed to be dovetailed with majors from other disciplines. The alternative major potentially sacrifices rigor for flexibility, although all evidence points to that flexibility simply allowing a wider range of opportunities with no loss of rigor whatsoever. The chemistry major going forward will be designed to insert flexibility while retaining (possibly enhancing) rigor. Chemistry majors are granted more advanced placement than we routinely allowed in the past. The flexibility also comes in the form of electives, for which core graduate level courses play a central role. This will come at a cost. The typical chemistry major may give way to more thematic (and uncertified) chemistry majors. Some will lean toward organic chemistry or biochemistry. Others may favor physical chemistry, chemical physics, or theoretical chemistry. The program is being designed to flex with changes in chemistry's needs and directions as well as its role in a nonchemistry professional world.

II. Curriculum.

We can best describe the current chemistry major in the context of the former major. While these courses do not provide an exhaustive review of the department's offerings, they serve as a useful starting point. Not surprisingly, assessment will be of paramount importance. Even that process is evolving contemporaneous to the curricular changes.

A. Chemistry 2070–2080 – *General Chemistry.* An introductory course for pre-meds, chemistry majors and biology majors. It provides a general exposure to a vast array of chemical topics including stoichiometry, gas laws, atomic structure, bonding, states of matter, chemical reactions, periodic properties, thermochemistry, thermodynamics, equilibrium, electrochemistry, kinetics, and colligative properties. It would be highly recognizable by almost any major chemistry program in the country. The two semesters provide an adequate background for chemistry majors and are ideally suited for those coming from high school who are not yet proficient in chemistry (as judged by advanced placement exams) as typically found for students with a single year of high school chemistry. Petrucci et al.'s *General Chemistry: Principles and Modern Applications* is a representative text.

B. Chemistry 2150 – *Honors General and Inorganic Chemistry.* An honors introductory course intended for chemistry majors. This sequence is populated with highly proficient students, uniformly having two years of high school chemistry as well as high scores and resulting credits on advanced placement exams. The mathematical rigor and pace are at a higher level than the standard general chemistry sequence. Although it does not formally require calculus, the students in this course have high school calculus almost without exception. The first semester focuses on standard freshman chemistry topics (thermochemistry, thermodynamics, equilibrium, electrochemistry, kinetics, colligative properties, nuclear chemistry). Zumdahl's *Chemical Principles* is a representative text whereas second semester is heavily derived from customized notes. With an advanced inorganic course (Chemistry 4100) already in the sequence, the single semester allows the students to proceed to organic chemistry in their second semester. Thus, official sanctioning of advanced placement represented the first gain in flexibility to be exploited for electives. Advanced placement is also inspires strong students to follow the highest level sequence instead of choosing the more conservative 2070–2080 sequence.

C. Chemistry 357–358 – *Organic Chemistry for the Life Sciences.* An intermediate course for chemistry majors—approximately half of our majors come through this sequence currently—typically taken by students who have taken a standard (non-honors) introductory sequence. This is a large service course that would be familiar to many across the country. Loudon's *Organic Chemistry* is a representative text. In the first semester, the basic principles of bonding, reactivity, nomenclature, and functional group transformations introduce the students to the most fundamental principles of organic chemistry.

The second semester focuses more on how to use organic chemistry and introduces the interface of organic chemistry with other fields including biochemistry and material science.

D. Chemistry 3590–3600 – *Honors Organic Chemistry I and II.* The curriculum the honors organic sequence is similar to that of the more standard sequence that is scheduled to follow directly from honors freshman chemistry (Chem 2160). The strength of the students, however, allow the course to move more briskly and into greater depth and understanding. Bruice's *Organic Chemistry* is a representative text. The sequence is completed at the end of the first semester, sophomore year, which naturally (but not necessarily) leads to Chem 4100 (below).

E. Chemistry 4100 – *Inorganic Chemistry.* This course offers a systematic study of the synthesis, physical properties, bonding, and reactivity of inorganic and organometallic compounds. It is of a sufficiently high level that the graduate program considers it an adequate course for students who will not be specializing in inorganic, organometallic, or materials chemistry. For students in the honors sequence, this will naturally become the fourth semester course. The students coming through the intermediate-level sequences will take it in their junior year. *Inorganic Chemistry* (4th ed) by Miessler and Tarr is a representative text.

F. Chemistry 3890–3900 – *Honors Physical Chemistry I and II.* The intermediate and honors-level chemistry students converge in their junior year for two semesters of honors physical chemistry. It is taught at the level of McQuarrie and Simon's *Physical Chemistry: A Molecular Approach*. The course demands both understanding and application of calculus to problem solving. The typical curriculum covers a range of topics, which invariably includes kinetics, thermodynamics, quantum mechanics. The course includes a strong computational interface using programs such as Mathematica and Igor Pro routinely.

G. Chemistry 2510, 3010–3030 – *Advanced Laboratories.* A sequence of laboratories loosely described as analytical chemistry, organic chemistry, physical inorganic chemistry, and physical chemistry are dovetailed throughout a four-semester sequence of labs. These methods include FTIR, UV-Vis, and NMR spectroscopies, gas chromatography, optical microscopy, fluorimetry, coulometry, and titrimetry. The major theme is to expose the students to the primary analytical and instrumental methods in the context of problem solving and wet chemistry experiments. Written and oral presentations become prominent in the latter two labs of the sequence, with the approximately half dozen reports per semester presented in the format of a primary research study.

H. Math and Physics – We require two semesters of advance math (differential and integral calculus as well as topics in multivariable calculus and linear algebra). Most students take a third semester as an elective. In addition, we require two semesters of calculus-based physics. Although the preponderance of our chemistry majors take at least one course in biochemistry, it has not been a formal requirement to date. A semester of biochemistry taught outside the department is accepted as an elective.

I. Graduate Level Courses – The curriculum includes a number of electives to be chosed from our primary graduate level courses as well as related disciplines across the campus. The core graduate level courses include:

(i) organic chemistry [*Advanced Organic Chemistry* (Chemistry 6650) and *Synthetic Organic Chemistry* (Chemistry 6660)]

(ii) inorganic chemistry [*Advanced Inorganic Chemistry I: Symmetry, Structure, and Reactivity* (Chemistry 6050) and *Advanced Inorganic Chemistry II: Synthesis, Structure, and Reactivity of Coordination Compounds, and Bioinorganic Chemistry* (Chemistry 6060)]

(iii) physical and theoretical chemistry [*Quantum Mechanics I* (Chem 7930), *Quantum Mechanics II* (Chem 7940), and *Statistical Thermodynamics* (Chem 7950)].

(iv) analytical chemistry [*Advanced Analytical Chemistry I* (NMR Spectroscopy; Chem 6250) and *Electrochemistry* (Chem 6290)]

(v) chemical biology and biochemistry [*Principles of Chemical Biology* (Chem 4500), *Chemical Aspects of Biological Processes* (Chem 6680)], and *Physical Chemistry of Proteins* (Chem 6860)]

The students can fulfill the chemistry major by following a completely traditional path, using former requirements as electives. They can also follow a more customized path that, although not necessarily leading to certification, better suits specific career goals. Additional courses include electives (an advanced course in math, for example) that were carefully selected (and occasionally revised) by our curriculum committee to ensure the appropriateness to the chemistry major's mission.

III. Learning Goals and Objectives.

A. Goal 1: Allow students to delve deeply into one or more sub disciplines within chemistry.

Objective – One reaches a depth of study in which the really interesting, contemporary problems in chemistry begin to surface. The bright light begins to shine on real research problems—to show our students the essence of being a research chemist—through our graduate courses. We have concluded that the only way a chemistry major can address the breadth of our undergraduates' interests is through electives. These are listed in the curriculum section (vide supra).

B. Goal 2: Introduce flexibility into the chemistry major through lower specificity of the requirements.

Objective: We increased the flexibility of the chemistry major to allow for a sub speciation. It is our belief that not all theoretical chemists need two semesters of organic chemistry nor do all organic chemists need the full sequence in math or physical chemistry. The only way to make room within what is already a very demanding major is to reduce formal requirements and increase the use of electives. This was done by allowing electives to substitute for (1) one semester of freshman chemistry (using advanced placement; vide supra); (2) one semester of organic chemistry; (3) one semester of physical chemistry; (4) one semester of advanced laboratory; or (5) one semester of math. Advising is of paramount importance, the available electives are highly regulated and actually at an equal or higher level of rigor than current required courses. The choices being made have been monitored for every student.

C. Goal 3: Provide exposure to the large array of methods available to chemists.

Objective: Chemistry is driven by analytical, computational, and instrumental methods. They are akin to those in a carpenter's tool box. Exposing students to these methods, even at a cursory level, dramatically increases the understanding of how they are applied and lowers the barrier applying them at some later date. Thus, a broadly based exposure is paramount. For experimentalists, this includes instrumentation mentioned in the laboratory sequence (vide supra). Computational and numerical methods for processing data are useful almost irrespective of career path. Students should know how to prepare, characterize, and understand the physical and electronic properties of molecular materials.

D. Goal 4: Develop written and oral communication skills.

Objective: Students learn to communicate effectively about chemistry in written and oral presentations. Students present written solutions to problems on homework and exams that clearly convey their reasoning in all but the largest courses (especially the laboratory sequences). Opportunities for oral presentation are limited until one reaches the smaller advanced courses, especially the graduate level elective courses discussed above.

E. Goal 5: Foster proper data analysis.

Objective: Students in more advanced courses evaluate whether mathematical approximations are applicable to problems, and if so, use them to find the solution. They also assess whether secondary physical effects are small enough to ignore. Standard curve fitting, statistical analyses, and error propagation are a fundamental component of the advanced laboratory sequence.

F. Goal 6: Design experiments that determine chemical properties and reactivities.

Objective: Students must begin to develop higher-order deductive reasoning in the latter half of the chemistry major. Our advanced laboratory courses are especially oriented toward Socratic methods of teaching. Inserting graduate level courses as electives elevate the students to a level in which the contemporary problems and challenges are in plain sight.

IV. Assessment of Learning Outcomes

Chemistry has extant methods for evaluating the progress of chemistry majors and the rhythms of our curriculum. Additional methods introduced contend with the unusually invasive changes anticipated in the short term. They are as follows:

A. **Quizzes and Exams.** In the introductory courses, assessment is done primarily through quizzes and exams. These quizzes and exams may include both multiple choice conceptual problems and more complex problems requiring longer solutions. Of course, these particular evaluations probably trace back to Socrates in the flesh.

B. **Small Group Problem Solving.** In our freshman and sophomore courses we now emphasize peer-led small group problem solving sessions. These activities involve 2-4 students working at a white board with a graduate or undergraduate TA. Problem sets have been normalized across the large courses, and the TAs are trained to provide effective instruction. In addition to being excellent pedagogy the small group sessions provide excellent real-time feed back to the instructor, through the TAs as to how well the students are assimilating subject material.

C. **Homework.** Students in most courses do homework problem sets in which they apply the principles that they have learned to various physical situations. Homework is predominantly a learning opportunity, and its use as an evaluation tool is largely formative rather summative. Students are encouraged to work together. In undergraduate courses, the skills learned through homework are tested through exams and quizzes.

D. **In-class Questions.** The introductory lecture courses make extensive use of real-time, in-class questions, often enabled by electronic technology (e.g. Learning Catalytics Software) in which the students vote on the answers to multiple-choice problems that test their understanding of the ideas being presented. By seeing how the students respond, the lecturer is instantly able to spot misconceptions and tune her lecture accordingly. This tool is also powerful for the students, since it gives them instant feedback on their comprehension.

E. **Lab Reports and Oral Presentations.** In the introductory courses, students turn in lab reports in which they answer a sequence of questions that take them through the experimental process. In the intermediate and advanced laboratories, students submit written laboratory reports that are similar in structure and content to journal articles. Some laboratory courses also ask that students present their results orally to the class. Student learning in these courses is assessed based on these written and oral reports.

F. **Projects.** In some courses, students carry out a project, usually leading to a paper or oral presentation. These projects test the ability of students to learn about a particular topic in detail, their ability to learn independently, and their skills at written and oral communication. They are graded based on criteria such as scientific accuracy and clarity of presentation.

G. **Honors Research.** Most of our certified chemistry majors carry out undergraduate research. In their senior year, many participate in our Honors Thesis Program (Chem 4980) in which they prepare a senior thesis and presenting a half-hour seminar. The oral presentation is evaluated by both the faculty member in charge (usually a younger professor) as well as their peers. The course also includes seminars by chemistry faculty covering a range of topics from writing papers and proposals, preparing seminars, life as a faculty member, the pursuit of tenure, and industrial career opportunities. With added flexibility of the major we anticipate expanded participation. Honors research in conjunction with GPA are used to determine Latin honors at graduation.

V. Assessing and Refining Teaching and Curriculum

One of the key components of a good curriculum is quality teaching. We have a highly active teaching evaluation committee that reports to the Associate Chair.

A. Teaching Evaluations. All courses are evaluated by student questionnaires that are subsequently monitored for strengths and weaknesses. Newer electronic evaluations allow for tailoring of questions to recent innovations or changes of a given year. Although absolute numerical scores have their limitations, written responses are usually beneficial for gauging student assessment. The lecturing skills and content of every assistant professor are evaluated by *two* independent visits per semester throughout their first five years at Cornell and discussed in a tenured faculty meeting each year. Evidence of problems in the performance of a tenured professor also triggers analogous in-class evaluations by the teaching evaluation committee. We have, on occasion, employed professional help in rehabilitating a sliding performance of tenured professors. Although our two lecturers are also evaluated, rarely are our majors taught by lecturers.

B. Teaching Assistant Training Program (TATP). Over 30 years ago, we sought funds for a summer training program for graduate students preceding their first year of graduate school. The pre-graduate students are trained in experimental and lecturing techniques, motivational methods, language development, and assorted other important activities such as CPR and first aid training. This month-long program has now been adopted by all departments in Cornell's College of Arts and Sciences, but most departments only do this for the foreign students. All of our foreign students and in excess of 90% of our entering domestic graduate students participate in summer training course.

C. Undergraduate Teaching Aids. Because of the sophistication of our advanced laboratory curriculum, we have begun employing chemistry majors in their senior year to assist the graduate teaching assistant. The undergraduates have no grading responsibilities nor are they in charge of a laboratory section; they are there to assist with the experiments and, as an added perk, learn how to teach a lab. They are paid with cash, not credits.

D. Stemming Grade Inflation. Approximately 30 years ago we made a subtle but consequential addition to our grading practices by imposing GPAs in the freshman and sophomore level chemistry courses. As a consequence, the average grades in the freshman and sophomore classes reflect the student's relative performance and these curves have not changed in recent years.

E. Assessing Large Scale Changes to Course Structure. In some cases, where course structure is dramatically altered (e.g. a flipped version of general chemistry). We have administered controlled examinations in subsequent years of instruction. In such a circumstance, a very similar exam is given in back-to-back years, before and after the teaching innovations have been implemented. Such experiments have been useful for gauging the effects of the course changes.

F. Progressive Improvement. In generally Chemistry courses, we have also implemented a measure we call "progressive improvement", which evaluates a student's improvement from an early prelim in an introductory course to either the exam final or the overall course performance. A prelim, taken after a few weeks into a course can be a reasonable pre-assessment of entering knowledge. For example, using this metric we were able to validate that the small-group peer-led learning was a more effective pedagogical tool than previous take-home homework problem sets or on-line learning platforms.

VI. Monitoring Student Responses

A. Curriculum Committee. Our curriculum committee during quiet periods oversees the curriculum and answers to the Associate Chair. They do, however, monitor choices being made by students in their electives and recommend omissions and additions to the electives.

B. Monitoring Student Choice. An increasing flexibility of the curriculum has generated a flood of fresh data. By monitoring what choices students are making flexible menu of options we have seen no evidence whatsoever that they are choosing easy paths. In a sense, the lack of change with the new curriculum is most notable. We have found that:

(i) the honors freshman chemistry course (Chemistry 2150) and affiliated advanced placement is popular.

(ii) Students remain conservative in their use of electives. They largely follow the traditional chemistry major with only occasional exceptions.

(iii) The total number of chemistry majors has held firm if one compares the new major to the previous two-tiered major.

(vi) Monitoring the performance of students in Chem 4980 shows interest in research to have remained steady.