

# THE EVOLVING NATURE OF CHEMICAL EDUCATION: Current and Future Potential

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In the early years of the new millennium, it might be useful to pause and look back to the 20<sup>th</sup> century (and earlier) to see what we have learned about chemical education. I take this as the focus for my remarks at the Singapore International Symposium on Chemical Education. The last millennium and the centuries before it have produced a number of useful lessons for us to consider here. If we are attentive, we may have the keys for improving chemical education in the 21<sup>st</sup> century. A number of the lessons are derived from empirical observations and, at least, one comes from outside of chemistry.

Perhaps the key lesson we—teaching chemists—have learned from the 20<sup>th</sup> century is that

- Chemistry has become the central science

(As an aside, the idea of “chemistry, the central science” was first made popular by Ted Brown who used it as the title of a general chemistry text [1] in 1977). Looking back, it’s obvious why chemistry has evolved into the central science. Because it’s principal focus is on understanding molecules and molecules make up the entire physical world, a basic understanding of chemistry has become important for progress in a number of, what could be called, the associated disciplines.

Very early, even before chemistry became a science, the chemistry associated with substances found in nature became important in establishing certain key chemical ideas. Early chemistry focused mainly on inorganic substances—substances derived from non-living systems. Some naturally-occurring substances, called organic compounds, did not fit neatly into the patterns developed for inorganic substances. Berzelius decided that the chemistry of life—organic chemistry—was something apart from the chemistry that had led to the atomic theory. Berzelius invented the concept of “vitalism” which held that only living tissue could make organic compounds.

In 1828, the German chemist, Friedrich Wöhler, who was Berzelius’ student, produced urea from ammonium cyanate. Up to that time, urea was known only as a compound found in urine, and ammonium cyanate was an inorganic compound. Wöhler’s discovery removed the psychological barrier against *synthesis* of organic compounds. Up to that time, synthesis implied “production from the elements”. Indeed, Berzelius, although he recognized Wöhler’s accomplishment, described the urea produced from the thermolysis of ammonium cyanate as “artificial urea” as if it really wasn’t the “true” urea. Philosophically, Wöhler unleashed chemical thought toward compounds associated with biological processes and the field of biochemistry was born.

Chemical thought has produced the subject, which is currently called molecular biology, a subject that, arguably, can be traced to the recognition of the genetic code by Crick and Watson in the early 1950s. Watson was trained as a biologist and Crick as a physicist, but their insight came from the application of chemical concepts. My point here is not to delineate the history of biochemistry, but to illustrate how chemical concepts, usually considering the implications of molecularity, have transformed whole disciplines. A similar evolution can be found for the silicon-based chip developments, which are derived from the ways physical properties of pure substances are affected by minute impurities as interpreted at a molecular level. We see similar incipient developments in the cognitive sciences with the tracing of brain function by nmr spectroscopy, which images either hydrogen or carbon environments at a molecular level[2]. We can develop similar connections to progress in other disciplines, but that would be over killing the main point, namely, that chemistry is the central science—an important lesson that was concluded in the 20<sup>th</sup> century and from which other lessons flow.

The centrality of chemical thought—its power to help in the solution of problems—has drawn increasing numbers of students into the system of chemical education, which I define as all chemistry instruction from pre-college teaching to postdoctoral teaching that some call “research”. This attraction has several manifestations—some good and some not so good. Among the latter—not so good—are the increasingly large enrollments found in general chemistry and organic chemistry courses. Indeed, at some institutions even physical chemistry courses can be described as “large,” i.e., multi-section courses of several hundred students. “Large” is not necessarily bad, but in many cases it leads to having to deal with students who may not have the characteristics for success in studying chemistry that seemed to be prevalent in earlier times. In recent times, many institutions recognize the existence of a class of students generally described as “under prepared.” A number of different kinds of rather extensive surveys have been used to describe the under prepared student:[3]

- 86.8% of the surveyed schools report that their students’ weaknesses in math skills were increasing.
- 39.5% reported their students had a weak high school chemistry background.
- 58.1% reported incoming students lacked inductive and reasoning skills.

In the United States, high attrition rates in college chemistry have been attributed to the poor preparation of students.[4,5] Another study listed pre-college preparation as one barrier to success in quantitative first year courses.[6] That study reported that only 35% of incoming students had sufficient math and science preparation to move directly into courses designed for science, mathematics, and engineering majors.

Many incoming students exhibit unrealistic expectations, and the lack responsibility, motivation, and study skills.

- Time management skills are often cited by researchers and students as a common problem.[7,8]

- Note-taking skills of students are important contributors to attrition. Students have problems distinguishing “relevant” from “irrelevant” information.[9]
- Studies have shown that students do not spend enough time to master the material. One survey of incoming students found that they expected to maintain an A or B average while spending only 6 or 7 hours per week, TOTAL, studying.[10]
- Generally, students are overconfident of their abilities and have unrealistic expectations.[7]

Some studies [8,11] attempted to differentiate between successful and unsuccessful first-year students. Factors that were identified in this survey were:

- Much heavier workloads at the university level than in high school.
- Self-motivation.
- Organizational skills.
- Effective study habits.
- Difference in academic standards between high school and university studies.
- “Studies” were not top priority. “I let my studies slide, always thinking I could catch up.”

Now, you should realize that my point here is not to deprecate students; rather, it is to describe the demonstrated characteristics of incoming students—at least in the United States. Not all under-prepared students have all these problems, but under-prepared students are a cohort that incorporates these problems. In the past, that cohort did not exist explicitly, but a few individual students did have some of those problems. A few students with a few kinds of problems could be dealt with individually. But large numbers of students create serious problems. As I’ll develop a bit later in this discussion, another trend in chemical education is to respond to individual differences. Clearly, many of the factors mentioned above have little or nothing to do with chemistry, or, indeed, any science discipline. Yet, these factors dictate the success of our efforts to teach chemistry to an expanding cohort of science-oriented students.

A number of years ago, Shelia Tobias[12] warned us that the current crop of entry-level science students were not “dumb”, they were “different” and that the presentation and organization of entry-level science courses ought to respond to those differences. I should note that Tobias’ differences were focused mostly on the ways even good students interacted with the conventional presentations of science courses—especially the lecture component. Tobias’ study showed that demonstrably good students (those who were mature and successful in non-science fields of study) had great difficulties with the classical lecture-oriented approach to teaching chemistry and physics. There is no reason to believe that good science-oriented students would not have the same kinds of difficulties. Tobias attributed the apparent success of science

students in such an environment to the fact that they were “true believers”. They would succeed in science courses in spite of the instructional deficiencies in the system of science education. As true believers, they were motivated and would “adapt”; they would march through any fire, which was expected of them.

As the importance of chemistry, the subject, grew, the proportion of true believers who take chemistry decreased. For example, only about 2% of the students who take general chemistry at The University of Texas at Austin are chemistry majors. However, the time honored instructional methods are still used for 98% of the students (~6,000 students) who annually take entry-level chemistry courses. Among the latter are students with the spectrum of personal characteristics discussed earlier. Is it surprising that the majority of students who take entry-level courses are going to have serious difficulties with completing these courses successfully? Such difficulties will be reflected through the system of education and will, undoubtedly, clash with the evolving philosophy of making science available to all citizens. Now, I don't want to sound elitist, but an analysis of America's needs for scientists [13] suggests that only about 1% of the higher education cohort of students are necessary for the science and technology needs of the nation. Yet, there is a drive to expose more students to the processes of science—for very good reasons. For example, a long-standing philosophical position states that a democratic society needs educated citizens, and a democratic society heavily dependent on technology needs citizens who know the bounds of science (a critical precursor to technology). It is especially important for educated citizens to know what science *can't* do.

So here's another lesson from the 20<sup>th</sup> century.

- An understanding of chemistry is necessary for an ever-increasing cohort of citizens. Those who *would* be scientists as well as those who would not, but who will be leaders in their chosen fields.

Let's turn our attention briefly to pedagogy. The way we teach chemistry—through a combination of lecture and laboratory—is based on the methods devised by the teaching chemists of the early 19<sup>th</sup> century. The apparent need for laboratory instruction has been commonly traced to Liebig, who observed[14]:

“At that time, chemical laboratories in which instruction was given in analysis did not exist anywhere; what people called such, were rather kitchens, filled with all sorts of furnaces and utensils for carrying out metallurgical or pharmaceutical processes.

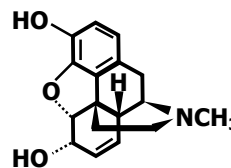
Nobody understood how to teach analysis.”

~~Liebig

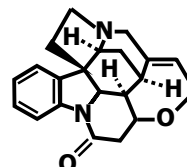
Liebig was clearly interested in analyses—the proportions of compounds that could be attributed to the elements present in the compound. Liebig, together with Wöhler, defined the early days of what is now called organic chemistry. In 1824, Liebig began to teach at the university in the small Hessian city of Giessen. There, he proved himself to be one of the great teachers of all time. He established a laboratory for the general student (an innovation at the time) and was the intellectual father (and grandfather) of most of the chemists since his time. Giessen became the chemical center of the world and maintained that position for a quarter of a century. We may wonder, why all this activity in the laboratory? My own analysis is that Liebig, whose chemical

interest was the burgeoning field of organic chemistry, needed analysts—chemists capable of producing percent composition data at high levels of precision. Such information was important to the development of the subject because it was the basis of the creation of formulas, e.g.,

- Morphine is  $C_{17}H_{19}O_3N_2$  and has the structure



- Strychnine is  $C_{21}H_{22}O_2N_2$  and has the structure



Formulas transformed words—morphine—which are arbitrary descriptors of substances into chemically significant descriptors. It was only through formulas of organic compounds that the great structural concepts of organic chemistry were revealed, for example, the concept of organic radicals (like  $CH_3$  and  $C_6H_5$ ) and functional groups. Simply put, Liebig needed well-trained and dependable workers to produce the data necessary to advance the subject of chemistry. All students who studied chemistry irrespective of their interests, e.g., medical students, did analysis, which supported Liebig's interests in organic chemistry. In a sense, Liebig created the general research structure that obtains in chemistry today. That is, an undergraduate program that introduced novices to the details of laboratory experiences upon which a graduate program builds. Notice the lack of "concern" for science majors and non-science majors in this process; recall that these two groups are those that swamp the current instructional system.

We still try to associate laboratory experiences with the lecture portions of entry-level courses. Indeed, it is this attempt to connect the didactic, or *lecture*, component with the practical, or *laboratory*, component that generally creates great difficulties in the administration of entry-level courses. Attempts to integrate a laboratory experience with a lecture component, generally suffer from logistics that involve space, time, and the availability of qualified instructors. Also, there are intellectual difficulties associated with melding lecture presentations with laboratory experiences. For example: Should the subject be approached in lecture *inductively* (from the specific to the general), or *deductively* (from the general to the specific), and how does a laboratory experience fit into this development? The result is often an arrangement, dictated by logistics, that separates the practical aspects of chemistry (the laboratory) from the didactic presentation (the lecture). This separation is sometimes overt, in the sense that there is a separate general chemistry laboratory; sometimes, even if the laboratory and lecture components are both part of the same course, they are often *de facto* separated intellectually because of logistic constraints.

Here we have another lesson from the 20<sup>th</sup> century.

- The role of the laboratory in helping students learn chemistry must be (re)defined.

Even if a laboratory experience is only a small component of instruction, there is an enormous commitment of resources—human, space, and consumables to this element of instruction. We need to address seriously the question of the role of the laboratory in helping students learn

chemistry, if for no other reason than to not send the wrong (or mixed) signals to entry-level chemistry students. And such information may possibly be useful in organizing our instructional strategies. For example, it may be (at one extreme) that all serious learning in chemistry can be connected to appropriately designed laboratory experiences, a condition that could greatly change undergraduate chemistry instructional strategies.

None of these comments pertain to chemistry majors—the true believers—who will be the developers of the subject in the future. In this sense, Liebig's philosophy may still be applicable, but is it the route for students who will not be chemists?

The 1960s saw the first reports of the applications of interactive digital technology to the processes of chemical education—both teaching and learning. Since effective networking was inaccessible in those days, it's not surprising that the earliest uses of computing stressed helping teachers teach. Early uses of computing to help teachers involved the generation, distribution, and assessment of individualized quizzes and homework sets. The efficient delivery, grading, and record keeping had to wait until effective networking systems were developed. The point of this short digression into the history of interactive computing is that the earliest uses of digital technology were applied to a system of chemical education that had developed since Liebig; instruction in a laboratory-lecture format. As classes got larger, the lecture-laboratory format was augmented by smaller groups sometimes called “recitation” or “discussion” periods in an attempt to provide the basis for individual engagement with the details of the subject. Discussion sections are often conducted by inexperienced instructors, so that the students' success in such an environment is often dictated by the logistics associated with acquiring and deploying sufficient, qualified personnel, time slots, and rooms. In this environment, the quality of homework sets can become an important component in helping students learn. Thus, digital techniques that can create, distribute, grade, and keep records of individualized homework sets were a great aide to the classical structure of chemical education.

Digital techniques also were devised to augment laboratory instruction, in effect, extending the range of experiences that conventional laboratory instruction was able to provide. Indeed, the creation of successful simulated experiences using digital technology began to raise questions about the viability and necessity of conventional laboratory instructional methods. The evolution of digital techniques to help teachers teach and students learn in the classic paradigm of chemical education led to the recognition that such educational processes were “better” when supported by interactive computing. “Better” was established empirically from several possible different viewpoints.

- Students achieved at a higher level using such techniques.
- Longitudinal studies suggested that students retained details longer.
- Students could cover a given body of information “faster”.
- Students had a better attitude concerning their studies of chemistry.
- Instruction could be delivered less expensively.

As experience grew with the use of digital technology, it became increasingly obvious that the system of chemical education could undergo significant changes. The FIPSE

Lectures[15] summarized those potential changes. I'll try to summarize the conclusions reached by the FIPSE lecturers.

- Because technology can accomplish much of what teachers used to do (mechanically), more time will be devoted to curricular issues and the curriculum will evolve constantly.
- Lectures will be fewer.
- The curriculum will become more laboratory-centered.
- Laboratory instruction will be more flexible.
- Learning will become more active.
- Books will be thinner.
- Examinations will be different.

In the years that have passed since the FIPSE Lectures were first published, a number of the predictions contained therein have begun to materialize, but going into these in detail would prolong this discussion without adding much more substance to the points I want to make.

By itself, technology has begun to alter the way chemical education is being done.

- Classroom lectures are being replaced by individual explanations driven by PC networks accessing much more information than can be delivered in a conventional lecture format.
- The passivity of students sitting in large lecture halls is being displaced by virtual apprenticeship-like programs.
- Individual work is being replaced by team learning.
- The omniscient teacher is being replaced by teacher as guide.
- Immutable content is being replaced by content that can be changed rapidly. This condition is consonant with the rapid changes that occur in the subject of chemistry.
- A homogenous curriculum is being replaced by a diverse curriculum. One size need not fit all.

These observations lead to the next lesson.

- Digital technology can form the basis for building useful tools to help teachers teach and students learn.

These results would seem to suggest that great progress has been made in chemical education. However, chemical education does not exist in a vacuum. As chemical education does not exist unconnected to the progress of chemistry, the subject, it cannot exist unconnected to the progress of our colleagues in educational psychology and the cognitive sciences.

If we broaden our view of chemical education, the work of educational psychologists and cognitive scientists comes into view almost immediately. In the last 25 years or so, our colleagues in educational psychology have made enormous strides in understanding the characteristics of learners. You remember the learners, the “other part” of the equation that recognizes that education has two components, teaching and learning. Teaching chemists who develop and support the use of technology seem proud of the fact that technology-based techniques can produce a high level of individualization. That’s the new frontier in chemical education. What’s the implication of producing an environment that is learner-centered instead of teacher-centered?

“One size fits all,” seems to have been the paradigm that evolved from the classic structure of chemical education. The implications of the promise of producing a learner-centered environment lie in understanding the importance of individual differences in learning styles. As so often is the case, progress in chemistry is triggered by the recognition by some chemists of progress in associated disciplines. I illustrate that kind of relational progress by the evolution of nuclear magnetic resonance, a phenomenon discovered by physicists. The early physicists who predicted and discovered the phenomenon were puzzled by the fact that the resonance signal for hydrogen seemed to depend on the substance. Liquid hydrogen gave a different resonance signal than, e.g., chloroform. We now recognize this as a chemical shift difference. It took chemists—scientists trained in molecular concepts—to recognize and exploit the chemical shift.

So it will be with the interaction of chemical education with the research results of educational psychology and the cognitive sciences where the importance of individual learning styles has been revealed.[16] Teaching chemists now must *apply* these revealed principles to their teaching needs because our colleagues in educational psychology and cognitive sciences have teased out the principles—and they are not necessarily interested in the *applications* of these in specific disciplines like chemistry. Recall that this is a common attitude in other disciplines, (e.g., the physicist who is happy to be able to discover and understand the resonance signals of nuclei, but is not particularly interested in the chemical shift concept, or the chemist who works diligently to describe and understand electronic effects in aromatic systems, but leaves it to others to apply the basic ideas to the synthesis of pharmaceuticals). One of the keys to the effectiveness of the uses of technology in chemical education lies in the recognition by the teacher and by the student that all people have strengths and weaknesses in their learning styles. Much of the frustration of integrating instructional technology into the curriculum results from trying to make technology work in the context of a narrowly defined view of intelligence and assessments of learning. The promise of educational technology is that it allows teachers to treat students as individuals with varied backgrounds, attitudes, and needs. But the current system of education, for the most part, is driven by a mass production philosophy—one size fits all. Clearly it is difficult to treat students as individuals if they are not seen as individuals.

All this is to recognize still another lesson learned.

- Educational psychologists and cognitive scientists *do* have something useful to say to teaching chemists.

## **SUMMARY**

What lessons have been learned in the previous centuries that have the potential to shape the details of 21<sup>st</sup> century chemical education?

- Chemistry *is* the central science.
- Digital technology *is* effective in helping students learn.
- The role of laboratory experiences in learning chemistry still must be defined.
- Educational psychologists *do* have something important to say to teaching chemists.

These are the lessons that we can exploit in the 21<sup>st</sup> century to make chemical education more effective to an increasingly larger number of students who have a legitimate interest in understanding some aspects of our science, but who will not be chemists in the classical sense.

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