Chemistry Education Research

prepared by

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Introduction

Chemists are increasingly aware that, although chemistry knowledge is a necessary condition for teaching excellence, it is not sufficient. College and university faculty worry openly about the demise of teaching and an over-emphasis on research. In response to such concerns, departments of chemistry have hired chemistry educators to provide leadership in chemistry education. However, the same faculty who sense a need for colleagues whose scholarship focuses on teaching and learning rather than generating new chemistry knowledge often have difficulty evaluating the work of chemistry educators. Are chemistry educators, like other university chemists, teachers *and* scholars or teachers only? If teachers *and* scholars, what kind of scholars are they? How does one Judge the quality of their scholarship? If they are teachers only, how does their teaching differ from the teaching that all academic chemists do?

It is in the spirit of recognizing diversity in higher education and rewarding excellence in all areas of scholarship that this paper was prepared.

Scholarship Reconsidered

> *[T]he most important obligation now confronting the nation's colleges and universities is to break out of the tired old teaching versus research debate and define, in more creative ways, what it means to be a scholar. It's time to recognize the full range of faculty talent and the great diversity of functions higher education must perform.* (Boyer, 1990, p. xii)

We agree with Boyer that “while we speak with pride about the great diversity of American higher education, the reality is that on many campuses standards of scholarship have become increasingly restrictive" (1990, p.2). It is time to broaden our definition of scholarship. Boyer describes *scholarship of teaching, scholarship of discovery, scholarship of integration, and scholarship of application* as four important areas of scholarship. We argue for a similar broadening within the chemistry discipline. Chemistry education, as a division of chemistry with the same status as inorganic, organic, physical, analytical, and biochemistry, includes these four definitions of scholarship. It is our purpose to describe chemistry education along these four lines.

Scholarship of Teaching

It is expected that chemistry educators will be, by definition, excellent teachers. Teaching is both an art and a skill. It is the skill part that should not be shortchanged in the definition. Chemistry educators integrate the findings of chemistry education research into their classrooms. They are aware of the needs of their audience, whether it is adult learners, science majors, non-concentrators, or young children, and they tailor their teaching to meet these needs.

University chemists often contend that one cannot be an effective teacher unless he or she is active in chemistry research. This is not necessarily so, and virtually every chemist can name at least one person to prove the point. We know, for example, many chemistry educators who have published no research other than their doctoral thesis but who have made important contributions to chemistry. They are sometimes more widely read and better informed than their research-active colleagues. They write insightful articles that clarify difficult concepts, they review books with charm and candor, and they assist authors of textbooks and journal articles who are struggling to communicate. Through their creative development of new demonstrations, laboratory experiments, and texts, they contribute directly to the instruction of thousands of students. They implement, in their own classrooms, the results of research carried out by their colleagues who do research in chemistry education. Theirs is the scholarship of teaching.

Scholarship of Discovery

Without carefully controlled experiments, it is impossible to draw conclusions relating cause to effect with acceptable confidence. In some instances of highly interrelated systems such as atmospheric chemistry or unique learning situations, not all variables have been identified and, therefore, cannot be adequately controlled. In these cases, naturalistic research is a first step in investigating the complex system. Still, controlled experiments have served science well, and they are as valuable in chemistry education as in the rest of chemistry research. *Research in chemistry education utilizes controlled experiments whenever possible, but it may rely on observation in naturalistic settings when insufficient knowledge of the system or limitations on the ability to manipulate human beings is a factor.* This is the scholarship of discovery.

Chemists synthesize new compounds and describe their properties; chemistry educators develop new teaching materials or instructional techniques and evaluate their impact. *Some research in chemistry education synthesizes and characterizes new instructional materials and techniques.* This is also scholarship of discovery.

Scholarship of Integration

The scholarship of integration includes the fact that much of chemistry education research informs theories of other disciplines and vice versa. Where the focus of research is how students learn chemistry, the guiding theories are drawn from "cognitive science," the catch-all label for application of information processing, artificial intelligence, or psychological theories to the study of cognition. Recently, qualitative studies of misconceptions in chemistry, problem solving, and the growth of conceptual understanding have drawn heavily on the techniques and theories of anthropology, sociology, and social psychology. Although these theories are identified with other areas of scholarship, research in chemistry education contributes to the elaboration and refinement of the theories. *Some research in chemistry education generates or refines learning theories, theories of social behavior, and models for instruction, but always with the goal of enhancing the transmission and understanding of chemistry.*

Scholarship of Application

The scholarship of application is applied research. It includes course improvement, curriculum reform, and implementation of instructional innovations when they are accompanied by the careful collection and interpretation of data that characterize all research. Applied research in chemistry education also concerns itself with comprehension, visualization, the construction of ideas, and other processes required to understand chemistry. Such research explores the interface between chemists, who generate new knowledge about the physical environment, and others in society, who generate the social, political, and economic environment in which chemists work. When done with scholarly care, chemistry education provides a feedback loop that benefits chemists and society at large. It benefits society by translating chemistry knowledge into terms that can be understood and used by lay persons and professionals in other fields as well as by chemists-to-be. It benefits chemists by increasing public understanding of their endeavors to a level that results in general support of their work. So that such benefits may accrue, *chemistry education research in these areas includes development of theoretical underpinnings, data collection, and generalization of results as would be expected of any applied research.*

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The Domain of Chemistry Education Research

Although it is impossible to describe all of the activities that might constitute research in chemistry education, it will help to define the domain of chemistry education. On the one side we need to distinguish research in chemistry education from other research in chemistry. On another side we need to distinguish *research* in chemistry education from other chemistry' education activities.

Just as there may be considerable overlap among research conducted by a solid state chemist, a materials engineer, and a solid state physicist, there may be overlap between the research of a chemist and that of a chemistry educator. Both, for example, might develop computer software for molecular modeling. Both would face similar problems of representing molecules on the computer screen, of manipulating the models in real time, and so forth. The difference would be in focus and goal. The chemist's focus would be on using the modeling software to predict reactivity, explain reaction mechanisms, and to guide synthesis of new compounds. The chemistry educator's focus would be on using the software to clarify basic concepts and principles, to explore how students construct their own mental models of molecular structure, or to optimize molecular representations for better understanding.

Because their focus is different, the chemist and chemistry educator ask different questions, collect different data, and use different techniques to analyze data. Their studies and conclusions are guided by different theories, and their results shape different theories. Still, there are areas of commonality.

Characteristics of Research

All research, regardless of the field, has common characteristics. We focus on just a few, comparing chemistry education research with other research in chemistry in the process.

Research is theory-based. Any research must eventually be related to theory. Theories provide the basis for hypotheses, some that are consistent with theory and some that are not, and these alternative hypotheses lead to predictions that can be tested to see if the theory holds. The world is far too complex to understand without ideas that unify what would otherwise be random observations.

Some research is directly related to the development or refinement of theory. In preparing this paper we examined fifty articles in the *Journal of the American Chemical Society* and found that approximately 20% of these articles dealt with theories and models. These articles seldom generate new theories, but, rather, verify existing ones or apply accepted theories to new systems. The same can be said about research in chemistry education.

In one respect theoretical articles in chemistry education differ from those in other branches of chemistry — the articles on theoretical chemistry are almost all computational chemistry; those on theoretical chemistry education are almost never computational. The subject matter of chemistry tends to hold still, making mathematical description somewhat easier than in the case of chemistry education. Chemists operate under the assumption that a collection of hydrogen molecules today is indistinguishable from one assembled fifty years ago. However, student bodies change from semester to semester, and students are exposed to countless influences that are difficult to describe as mathematical variables.

Research is based on data. Research involves data collection. It does not always involve numbers, but it does involve data. In the review of JACS we classified 16% of the articles as synthesis and characterization of compounds, some of which were originally formed by accident. Does such serendipitous synthesis of a compound constitute research? We think not, but when a chemist reconstructs the conditions that produced the compound, carefully noting factors such as temperature, amount of light, presence of other materials, and whatever else might have affected the outcome of the reaction, it is research. Now there are data, which others can use to verify the result and repeat the experiment.

Consider an analogous case in chemistry education, one that could be planned or accidental: A lesson on entropy is presented and, even though it is their first exposure to the subject, students understand the concept. Both teacher and colleagues would be ecstatic at such an occurrence, but would they call it research? Probably not, regardless of how often this teacher could repeat the lesson. However, when the chemistry educator reconstructs the conditions that led to success, carefully noting factors such as how the topic was introduced, the sequencing of ideas, students' attitudes, the nature of interactions among students and between students and teacher, the experiments or demonstrations used, and the sequence of events in the lesson, that /s research. Now there are data, which others can use to verify the result and repeat the lesson.

Research produces generalizable results. Research uses experiment and observation. There is no more powerful tool for research than the controlled experiment. By setting conditions so that all variables are fixed, save two, we can manipulate one and observe how the other responds until we can connect cause with effect. But there are times, in chemistry and chemistry education, when variables are unknown, cannot be controlled, or interact in such complex ways that controlled experiments produce unnatural behavior, meaningless observations, or misleading data. In cases such as the study of atmospheric chemistry or classroom. learning, we are forced to rely on observations carried out in natural settings. Qualitative research techniques borrowed from anthropology and other social sciences are used with increasing frequency by chemistry educators. The focus of that research is to identify variables that affect learning in classroom settings, and the hope is that those variables can be identified and understood, making it possible to verify their effect through controlled experiment. But limitations on freedom to manipulate human beings, the object of study for chemistry educators, results in the fact that *observation in naturalistic settings will always be an important tool for chemistry education research.*

Physical Chemists look at the dynamics of chemical change and the mechanisms through which that change occurs. (Thirty-six percent of the JACS articles we reviewed fall into this category.) Similarly, chemistry educators study the dynamics of classrooms, sometimes focusing on the rate of learning under different conditions, sometimes examining the mechanisms through which the change occurs. *Some research in chemistry education examines the process of learning in classrooms and in individuals in an effort to understand and enhance that learning.*

Summary

Through this examination of research in chemistry education we have shown that, although the techniques and guiding theories differ from those used in other branches of chemistry, the intent is the same. As Bridgman puts it, "the objectives of all scientists have this in common — that they are all trying to get the correct answer to the particular problem in hand" (1945/1950, p. 342).

Many "problems in hand" are not resolved through traditional research, and we repeat Boyer's admonition that "It's time to recognize the full range of faculty talent and the great diversity of functions higher education must perform" (1990, p. xii). Toward that end scholarship of teaching, scholarship of integration, and scholarship of application in chemistry education were discussed along with scholarship of discovery. We do not wish to suggest that all chemistry educators should be doing research, even of the applied nature. Neither do we wish to imply that only those who do research should be rewarded. But our charge was to clarify chemistry education research so that chemists wishing to reward it may do so intelligently.

Judging research in chemistry education must involve the same considerations as judging any research: Is the work sound? Does it conform to accepted standards? Can one have confidence in the conclusions reached? But differences between research in chemistry education and other branches of chemistry — differences in goals, guiding theories, tools of measurement, and degree of quantification — also must be taken into account.

Teaching chemistry is as old as chemistry itself, but the identification of chemistry education as a subdiscipline of chemistry is not. Only during the last twenty-five years has chemistry education established a research base. Furthermore, chemistry education crosses disciplines, and as in other interdisciplinary fields — chemical physics, biochemistry, or materials science, for example — acceptance takes time. Although speaking about the acceptance of paradigms that shape scientific understanding rather than acceptance of new, interdisciplinary fields, Thomas Kuhn's comments in *The Structure of Scientific Revolutions* seem to apply:

> How, then, are scientists brought to make this transposition? Part of the answer is that they are very often not .... Priestley never accepted the oxygen theory, nor Lord Kelvin the electromagnetic theory, and so on. ... Max Planck, surveying his own career in his *Scientific Autobiography,* sadly remarked that "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."
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> ... Though a generation is sometimes required to effect the change, scientific communities have again and again been converted to new paradigms. Furthermore, those conversions occur not despite the fact that scientists are human but because they are. Though some scientists ... may resist indefinitely, most of them can be reached in one way or another. (Kuhn, 1970, pp. 150-152)

Kuhn points out that the ability of a new paradigm to solve problems that the old one could not are important to its acceptance. Similarly, the acceptance of chemistry education research depends on its ability to solve important problems that cannot be solved by physical, organic, inorganic, analytical, or biochemical research.

It is clear that chemistry education addresses important problems. There is an increasing need for broad scientific understanding in order to address public policy issues such as environmental pollution and resource management as well as for employment in a growing number of high-tech industries. As pointed out in the section on scholarship of application, chemistry education operates at the interface between chemistry and society. It helps chemists determine what knowledge society needs, and it investigates how chemistry is learned by chemists-to-be and society in general.

There was, perhaps, a time when the needs of chemists and society in general were well served by the small minority of citizens who studied chemistry and understood it. That is not so today. Without the understanding of how chemistry can be taught and learned that derives from research in chemistry education, the entire field of chemistry is impoverished and its contribution to humanity is reduced.

References

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