STATUS, CONTRIBUTIONS, AND FUTURE DIRECTIONS OF DISCIPLINE-BASED EDUCATION RESEARCH: THE DEVELOPMENT OF RESEARCH IN CHEMICAL EDUCATION AS A FIELD OF STUDY[1]

by

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Twenty years ago, Boyer (1990) called for an expanded definition of the term *scholarship* to include discovery, integration, application and teaching.

> The 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. (p. xii)

It is tempting to reread *Scholarship Reconsidered: Priorities of the Professoriate* within the context of the growth in recent years of what has become known as discipline-based educational research.

DBER: Neither New nor Easy To Identify

Discipline-based educational research (DBER) is not new. It is almost 60 years since the *Mathematics Teacher* perceived the need to introduce a column on "Research in Mathematics Education" to familiarize its readers with the results of mathematics education research (Kinsella, 1952). At roughly the same time, the National Council of Teachers of Mathematics issued the first in a series of biennial publications that contained lists of research studies in mathematics education (Kilpatrick, 1992). Only a year later, the AERA published the second of its "What Research Says to the Teacher" pamphlets, which was devoted to the topic of research that had been done on the teaching of arithmetic (Morton, 1953). By the end of the 1960s, Romberg (1969) was able to claim that more than 1000 studies of mathematics instruction had been reported.

Discipline-based educational research is not easy to unambiguously identify. Consider an *American Journal of Physics* paper (Arons, 1959) that was submitted for publication, summarily rejected as being "… of marginal interest to the readers," and then resubmitted when the editor's term expired. This paper described a innovative calculus-based physics course constructed around "… the idea of not doing too much too fast, leading the students to define, talk, verbalize, interpret, [and] connect with every day experiences" (Aron, 1998). This paper contained ideas that are still being advocated by physics educators more than 50 years later, but was it physics education *research*?

The field of discipline-based educational research now known as PER (McDermott & Redish, 1999) can be traced back to the work of individuals such as Arnold Arons, Bob Karplus, and John Renner that started in the late 1960's and early 1970's. Karplus became interested in applying Piaget's ideas at the K-12 level (Karplus & Thier, 1967), whereas Renner gained fame by noting that the majority of college-age students in introductory chemistry and physics classes were not able to successfully solve Piagetian tasks on the control of variables and ratio reasoning (McKinnon & Renner, 1971). With time, PER became the study of domain-specific tasks as a complement to traditional work in cognitive science (Resnick, 1983). It is difficult, however, to unambiguously separate recommendations by physics educators for which there is support from the research literature, such as "You have two ears and one mouth, and should use them in that proportion" (Arons, as cited in Feldman & Minstrell, 2000), from discipline-based educational research, *per se.*

What is Chemical Education Research?

Chemical education research (CER) (Bunce & Robinson, 1997; Herron, 1998; Herron & Nurrenbern, 1999) and PER (McDermott & Redish, 1999) emerged more or less simultaneously out of a long-standing commitment to improving education in the sciences that traces back to 1924, when the *Journal of Chemical Education* was launched by the nascent "Section of Chemical Education" of the American Chemical Society, or 1930 when the American Association of Physics Teachers was created "to be the leader in physics education."

The first volume of *JChemEd* (see Lagowski, 1998) contains articles that individuals familiar with recent literature might call prescient, including an article that called for "educating everyone," an analysis of the poor state of chemistry instruction in high schools, a tirade on the content of "current text books," and a paper entitled "What Kind of Research Is Essential to Good Teaching?" that argued for the need for chemistry teachers to engage in research (Patrick, 1924). Proponents of CER might be pleased by this early recognition of the connection between research and teaching until they note that the kind of research Patrick was advocating involved "… comb(ing) the subject of chemistry from end to end for facts and for methods of exposition that will make such facts live and real to his students." Occasional articles continued to appear in early issues of *JChemEd* that mentioned "research in chemical education," but not necessarily from a positive perspective. Reed (1929) noted that this field was "new" and that:

> The number of college professors … working in the field are few. In fact few college professors are competent to work in this field. Many college teachers know chemistry and despise pedagogical training or know educational principles and despise a thorough knowledge of chemistry. Research in teaching of chemistry by college chemistry professors is bound to be unpopular so long as college deans say 'we keep him (professor) as far as possible from all schools of education'. (p.565)

The development of an accurate history of CER is confounded by the challenge of differentiating between three sets of overlapping categories: (1) reports of *chemistry* versus *science* education research, (2) *descriptions* versus *reports* of educational research, and (3) reports of *research results* versus discussions of *theoretical frameworks* or *research methods*.

Consider the difference between a paper (Charen, 1963) that appeared in the first volume of the *Journal of Research in Science Teaching* (JRST), for example, and the most recent CER paper in the same journal (Cartrette & Bodner, 2010). The author feels confident in asserting that the recent paper by Cartrette and Bodner, which probes successful versus unsuccessful problem-solving by graduate students and beginning faculty within the domain of ^{1}H NMR and IR spectroscopy, is an example of chemical education research. Charen's paper, however, could easily be classified as an example of what was, at the time, the burgeoning field of science education research.

The second set of overlapping categories might be exemplified by comparing early CER papers published by Herron and co-workers that reported the results of research on the teaching and learning of chemistry (Cantu & Herron, 1978; Ward & Herron, 1981) with papers by the same author that addressed similar topics, but with greater emphasis on describing the implications of research on Piagetian stages (Herron, 1975, 1978).

Resolving the third dichotomy would require a set of standards for deciding whether reviews of discipline-based educational research should include papers that involve discussions of theoretical frameworks, such as constructivism (Bodner, 1986), research methodologies (Bowen, 1994; Nurrenbern & Robinson, 1994; Phelps, 1994; Pribyl, 1994; Bodner, 2004), and/or position papers on the scholarship of teaching and the field of chemical education research (Anonymous, 1994).

The Development of Chemical Education Research

In an attempt to provide an overview of CER, Herron and Nurrenbern (1999) noted that: "chemical education research is scholarship focused on understanding and improving chemistry learning," and noted that "publication of chemical education research — systematic investigation of learning grounded in a theoretical base — is a relatively recent undertaking." Another article that tried to define CER (Bunce & Robinson, 1997) argued that research in chemical education is "the third branch of our profession," and noted that chemical education researchers focus on a variety of research questions, such as "How and why do students learn? Why is chemistry difficult, even for many good students? What works to facilitate effective learning of chemistry?" Bunce and Robinson (1997) noted that CER can serve two audiences: "… those who want to better understand the problems involved in teaching and learning chemistry and those who want to know more about how such knowledge is obtained."

It is tempting to argue that the development of both PER and CER was facilitated by a change that occurred in the National Association for Research in Science Teaching in May, 1963, when NARST published the first issue of the *Journal of Research in Science Teaching* with the explicit goal of increasing the emphasis on *research* in science education (Joslin, et al., 2008). Articles that could be considered on the border between science education research and chemical education research soon appeared in *JRST* (e.g., Charen, 1963; Deloach, 1964; Rainey, 1965; Heindel & Leply, 1966, and so on). With time, there was a gradual shift away from the search for general truths that are valid across the disciplines of science, technology, engineering and mathematics toward content-based research that focused on the problems students and their instructors faced in teaching and learning individual disciplines, such as chemistry or physics.

Another change that accompanied the shift toward discipline-based educational research was a shift in the focus of this research from studies of elementary and secondary students toward work done with students enrolled in more advanced-level courses. Bodner and Weaver (2008) noted that research on the teaching and learning of chemistry was once done almost exclusively by faculty in schools and colleges of education who were hired to supervise pre-service teacher training programs. It is not surprising, therefore, that this research focused on the problems faced by elementary and secondary school students when they were exposed to chemistry for the first time (e.g., Cantu & Herron, 1978; Ward & Herron, 1978; Gabel & Sherwood, 194; Gabel, et al., 1984; Yarroch, 1985). Nor is it surprising to note that when the author of this chapter first attended NARST conferences he noted that papers that focused on the issues of teaching and learning at the tertiary level were rare.

Over a period of about 25 years, a fundamental change has occurred in the nature of research being done in chemical education as more of this research is being done by faculty with appointments in chemistry departments where they are responsible for teaching students at the tertiary level — in either large enrollment first-year courses (e.g., Bodner & McMillen, 1986; Herron & Greenbowe, 1986; Carter, et al., 1987; Nakhleh, 1993; Phelps, 1996), advanced-level courses undergraduate courses in biochemistry, organic chemistry, and physical chemistry (Moore & Schwenz, 1992; Zielinski, 1995; Towns & Grant, 1997; and so on), or special topics courses for graduate students (Bhattacharyya & Bodner, 2005). It should be noted, however, that this shift has not been easy to attain because of resistance from editors who have argued that work on advanced-level chemistry courses would be of only marginal interest to readers of their journal, or that readers of their journal would not understand this work.

The Development of Chemical Education Research Graduate Programs

It has been 30 years since a CER graduate program was created at Purdue University. Bodner and Herron (1984) justified the creation of a graduate program in chemical education on the basis that “scholarship seldom flourishes in isolation” (p.180). They noted that:

> The individuals most likely to carry out research in chemical education are found in two places: (1) departments of science education, where they often have little contact with chemists, or (2) in large chemistry departments, where they head the general chemistry program. In light of the administrative and teaching loads associated with large general chemistry programs, it is not surprising that the individuals who head these programs are likely to pursue *research in chemistry* that is understood, appreciated, and supported by their colleagues.” (p.180)

Bodner and Herron (1984) suggested that the term *chemical educator* had evolved over the years. When the *Journal of Chemical Education* was created, it was used to “... describe people who were first and foremost chemists, but who made contributions in many areas, including the teaching of chemistry.” With time, it was also used to “... describe individuals who primarily teach what others have discovered and who serve the multitudes who study chemistry as part of their education.” The Division of Chemical Education was created to recognize “... the emergence of a generation ... [who were] also likely to focus their attention on research about the teaching and learning of chemistry at all levels.”

The paper announcing the creation of the division of chemical education at Purdue suggested that “Only time will reveal whether what we have done represents a significant step in the growth and development of chemical education or merely an unimportant administrative reorganization in a single institution” (Bodner & Herron, 1984, p. 179). The best evidence that content-based educational research programs in chemistry now transcends the boundaries of a single institution can be found by noting that Ph.D. programs in chemistry education exist at Akron, Arizona, Arizona State, Clemson, Colorado State, Connecticut, Georgia, Iowa State, Kansas, Massachusetts - Boston, Miami, Montana, New Hampshire, North Carolina State, North Texas, Northern Colorado, Oklahoma, Purdue, South Dakota State, South Florida, Texas, Texas Tech, and UNLV (CER Resources, 2010).

Reporting/Publishing Chemical Education Research

Bodner and Towns (2010) noted that research in chemical education, at one time, was primarily reported at meetings of science educators, such as NARST or AERA conferences. In 1984, a half-day symposium on research in chemical education was included, for the first time, in the program at a national ACS meeting. That summer, a day-long chemical education research symposium was added to the program for the Biennial Conference on Chemical Education, for the first time, during the 8th BCCE at the University of Connecticut. Ten years later, at the 13th BCCE at Bucknell University, the chemical education research symposium lasted two days. Twenty years later, at the 18th BCCE at Iowa State in 2004, there were six half-day sessions devoted to chemical education research, with 35 papers from 20 different institutions, as well as papers on chemical education research in 10 symposia on other topics.

At one time, papers on chemical education research were published in *JRST* or *Science Education*. Eventually, a research in chemical education column was added to the *Journal of Chemical Education*. Today papers of this nature also appear in *The Chemical Educator*, in *Chemical Education Research and Practice* (published by the Royal Society of Chemistry as a continuation of a journal once known as *University Chemistry Education*), in *Biochemistry and Molecular Biology Education* (published by the ASBMB), and other journals as well.

Content-Based Educational Research in Chemistry

Bodner and Towns (2010) summarized the list of research topics undertaken by graduate students associated with the chemical education program at Purdue over a period of 30 years in a table organized into eight general themes: laboratory-based instruction, teachers' understanding, students' understanding, problem solving, alternative modes of instruction, computer-based instruction, research in advanced-level courses, and content-based research in other disciplines (See Table 1).

They noted that some of the work upon which these Ph.D. dissertations are based could have been done in traditional science education program by graduate students with a strong undergraduate background in chemistry. However, they noted that the creation of a division of chemical education within a large, research-oriented chemistry department facilitated the growth of collaborative research on the teaching and learning of chemistry in advanced courses that requires both extensive graduate-level training within the content domain for the individual doing this work and access to practicing chemists from the content domain who are willing to collaborate on research of this nature.

A brief description of several recent studies carried out at Purdue was created by Bodner and Towns (2010) to illustrate what can be achieved through collaborative, team-based, discipline-specific, content-based research. Gardner (2002), for example, had been a physics major as an undergraduate who went on to write an M.S. thesis in solid state chemistry before he started work toward his Ph.D. in chemical education. His dissertation was based on the following guiding research questions: "What are the experiences of students learning quantum mechanics?" "What conceptual difficulties do students have with quantum mechanics?" And, "How do students approach learning quantum mechanics?" This work involved extensive classroom observations as well as both traditional qualitative interviews and more loosely organized tutor-sessions/-interviews with students enrolled in either a quantum mechanics course for junior physics majors, the second-half of a physical chemistry course for chemistry majors, or a one-semester introduction to quantum mechanics taken by students from chemical engineering. It therefore required an interviewer with sufficient content knowledge to act as a tutor in quantum mechanics and to analyze the data that eventually produced insight into the phenomenon known as a "problem-solving mindset" that many chemistry students bring to quantum mechanics classes (Gardner & Bodner, 2007). Both the analysis of the data collected in this study and the validity of its conclusions were significantly aided by the presence on the dissertation committee of four faculty who not only taught physical chemistry but were active in doing research with this content domain.

During the course of her Ph.D. work, Orgill (2003) had the opportunity to teach half of the lectures in both a junior-level biochemistry course and a graduate-level course on biotechnology. She was therefore in an excellent position to complete a study of the use of analogies in biochemistry that involved classroom observations, analysis of biochemistry textbooks, and extensive interviews with both students and faculty involved in undergraduate biochemistry courses. She found that analogies are useful in promoting understanding, visualization, recall, and motivation in biochemistry students at all levels, and that students appreciate, pay attention to, remember, and use analogies their instructors provide. She found, however, that they would be even more useful if students understood what analogies are and how they can be used to improve understanding of biochemical concepts (Orgill & Bodner, 2004, 2006, 2007).

For more than 20 years (Pribyl & Bodner, 1987) we have been trying to understand why so many good, hard-working students struggle with organic chemistry. In recent years, we have probed the cognitive structures that facilitate the mental rotation of a two-dimensional representation of the structure of an organic molecule (Bodner & Briggs, 2005), and studied the factors that influence the ability of practicing organic chemists to solve problems that involve determining the structure of an organic compound from ^{1}H NMR and IR spectra (Cartrette & Bodner, 2010). Particular attention has been paid to understanding what the arrow-pushing formalism that is used by practicing organic chemists to convey the mechanism of a chemical reaction means to undergraduates (Anderson & Bodner, 2008; Ferguson & Bodner, 2008) and graduate students (Bhattacharyya & Bodner, 2005). This work on the teaching and learning of organic chemistry has been facilitated by the fact that Bhattacharyya, Cartrette and

Ferguson had all completed M.S. theses in synthetic organic chemistry before they began their work in chemical education, and that Briggs had been a practicing chemistry in industry before returning to graduate school.

The Future of Chemical Education Research

It is a rash individual who tries to predict the future. A few years ago, the author was asked to comment on research in chemical education as a career path, past and future (Bodner, 2005). It is not surprising that he spent a considerable amount of time on the past, with only a glimpse at what the future might bring. During his presentation the author raised several questions, the first of which was, "Why do research in chemical education?" The answer he provided was not original; it was part of the mission statement for the National Association for Research in Science Teaching for many years: "to do the research that informs instruction."

It is the author's firm hope that the future of CER will represent a tighter coupling between the results of this research and instructional methods that are used in practicing classrooms. This vision for the future was influenced by the consensus reached by science education researchers that research should play "… a key role in improving science education" (Kyle, et al., 1991), and that "… science curriculum reform should be *based* on research and *evaluated* by research (Shymansky & Kyle, 1992). It also reflects the argument presented by Slavin (2002), who noted the need for systematic research that informs instruction by providing rigorous evidence for the best practices for teaching specific educational context. This optimistic vision for the future is set firmly in the context of pessimism about what we have accomplished, so far (Gabel, 1999).

> Unfortunately, chemistry education research in the 20th century has had little influence on the way chemistry is taught … Although chemistry education researchers have identified common misconceptions for almost every topic taught in introductory science courses, probably nine out of ten instructor are not aware of these misconceptions or do not utilize ways to counteract them in instruction.

This vision for the future is partially based on the hypothesis offered when the future of CER was envisioned (Bodner, 2005): "Chemical education research is like research in any other domain of chemistry. It is the process, not the product that is important." At the time, this hypothesis was justified by noting that, "Implementing chemical education research programs is similar to calling for inquiry-based instruction in the K-12 classroom — it focuses attention on the process by which students learn, thereby making the researcher a better teacher." Some time ago, Peter Fensham (1985) called for "science for everyone." In much the same fashion, the author envisions a future characterized by the notion of *every* teacher a researcher (Bodner, MacIsaac & White, 1999).

At one time (Bodner, 2005), the author postulated that the future might include a dedicated *Journal of Chemical Education Research*, dedicated CER conferences, an ACS Award for Research in Chemical Education, and/or the publication of chemical education research in journals such as the *Journal of the American Chemical Society*, *Inorganic Chemistry*, the *Journal of Organic Chemistry*, and so on. It is a pleasure to note that progress has been made toward making these predictions come true. The ACS has created an award recognizing contributions to the field of CER, and the Royal Society of Chemistry has created *Chemistry Education Research and Practice* devoted to publishing the results of research in chemical education and/or descriptions of instructional practice based on a solid foundation of research on the teaching and learning of chemistry.

References

Anderson, T. L. & Bodner, G. M. (2008). What can we do about "Parker"?: A case study of a good student who didn't "get" organic chemistry, *Chemistry Education Research and Practice*, *9*, 93-101.

Anonymous (1994). Chemical education research. *Journal of Chemical Education*, *71*(10), 850-

Arons, A. B. (1959). Structure, methods, and objectives of the required freshman calculus-physics course at Amherst College. *American Journal of Physics, 27*, 658- 666.

Arons, A. B. (1998). Research in physics education: The early years. Based on a paper presented at the physics education research conference, Nebraska-Lincoln, 1998.

Bhattacharyya, G. & Bodner, G. M. (2005). “It gets me to the product”: How students propose organic mechanisms, *Journal of Chemical Education*, *82*(9), 1402.

Bodner, G. M. & Herron, J. D. (1984). Completing the program with a division of chemical education, *Journal of College Science Teaching*, *14*(3), 179-180.

Bodner, G. M. (1986). Constructivism: A theory of knowledge, *Journal of Chemical Education*, *63*, 873-878.

Bodner G. M. & McMillen T. L. B. (1986), Cognitive restructuring as an early stage in problem solving, *Journal of Research in Science Teaching*, **23**, 727-737.

Bodner, G. M., MacIsaac, D. & White, S. R. (1999). Action Research: Overcoming the Sports Mentality Approach to Assessment/Evaluation, *University Chemistry Education*, *3*(1), 31-36.

Bodner, G. M. (2004). Twenty years of learning: How to do research in chemical education, *Journal of Chemical Education*, *81*(5), 618.

Bodner, G. M. (2005). Research in chemical education as a career path: Past and future, Gordon Research Conference on Chemical Education Research and Practice.

Bodner, G. M. & Briggs, M. W. (2005). A model of molecular visualization. In J. K. Gilbert (Ed.), *Visualization in Science Education* (pp. 61-72). Dordrecht: Springer.

Bodner, G. M. & Weaver, G. (2008). Research and practice in chemical education in advanced courses, *Chemical Education Research and Practice*, *9*, 81-83.

Bodner, G. M. & Towns, M. H. (2010). The division of chemical education revisited, 25 years later, *Journal of College Science Teaching*, July/August, 38-43.

Bowen, C. W. (1994). Think-aloud methods in chemistry education. *Journal of Chemical Education*, *71*(3), 184-.

Boyer, E. (1990). Scholarship reconsidered: Priorities of the professoriate, The Carnegie Foundation for the Advancement of Teaching. Princeton, NJ.

Bunce, D. M. & Robinson, W. R. (1997). Research in chemical education: The third branch of our profession. *Journal of Chemical Education*, *74*(9), 1076-1079.

Cantu, L. L. & Herron, J. D. (1978). Concrete and formal Piagetian stages and science concept attainment, *Journal of Research in Science Teaching*, *15*(2), 135-143.

Carter C. S., LaRussa M. A. and Bodner G. M., (1987), A study of two measures of spatial ability as predictors of success in different levels of general chemistry, *Journal of Research in Science Teaching*, **24**, 645-657.

Cartrette, D. P. & Bodner, G. M. (2010). Non-mathematical problem solving in organic chemistry, *Journal of Research in Science Teaching*, *47*(6), 643-660.

CER Resources. (2010). Retrieved 11 October 2010 from: http://www.users.-muohio.edu/bretzsl/gradprograms.htm

Charen, G. (1963). The effect of open-ended experiments in chemistry on the achievement of certain objectives of science teaching, *Journal of Research in Science Teaching*, *1*(2), 184-190.

Deloach, W. S. (1964). Organic chemistry tests — an analysis, *Journal of Research in Science Teaching*, *2*(1), 51-57

Feldman, J. Minstrell (n.d.) “Action research as a research methodology for the study of the teaching and learning of science” p.8 online at http://www.unix.oit.umass.edu/~afeldman/ActionResearchPapers/FeldmanMinstrell2000.PDF.

Fensham, P. J. (1985). Science for all: A reflective essay, *Journal of Curriculum Studies*, *17*(4), 415-35.

Ferguson, R. L. & Bodner, G. M. (2008). Making sense of arrow-pushing formalism by chemistry majors enrolled in organic chemistry, *Chemistry Education: Research and Practice*, *9*, 102-113.

Gabel D. L. & Sherwood R. D. (1983), Facilitating problem solving in high school chemistry, *Journal of Research in Science Teaching*, **20**,163-177

Gabel D. L., Sherwood R. D. & Enochs L. (1984), Problem solving skills of high school chemistry students, *Journal of Research in Science Teaching*, **21**, 221-233.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education*, *76*(4), 4-

Gardner, D. E. (2002). Learning in quantum mechanics. Unpublished doctoral dissertation, Purdue University, West Lafayette, IN.

Gardner, D. E. & Bodner, G. M. (2007). The existence of a problem-solving mindset among students taking quantum mechanics and its implications In ACS Symposium Series, 973, *Advances in Teaching Physical Chemistry* (155-173). Oxford: Oxford University Press.

Heindel, N. D. & Lepley, A. R. (1966). The effect of nonrandomization of correct answer option in standardized chemistry examinations, *Journal of Research in Science Teaching*, *4*(4), 246-247.

Herron, J. D. (1975). Piaget for chemists. Explaining what "good" students cannot understand, *Journal of Chemical Education*, *52*(3), 146-

Herron, J. D. (1978). Piaget in the classroom. Guidelines for applications, *Journal of Chemical Education*, *55*(3), 165-

Herron J. D. & Greenbowe T. J. (1986). What can we do about Sue: a case study of competence, *Journal of Chemical Education,* **63**, 526-531.

Herron, J. D. (1998). Chemical education research. *Journal of Chemical Education*, *75*(12), 1537-1539.

Herron, J. D. & Nurrenbern, S. C. (1999). Chemical education research: Improving chemistry learning. *Journal of Chemical Education*, *76*(10), 1353-1361.

Joslin, P., Stiles, K. S., Marshal, J. S., Anderson, O. R., Gallagher, J. J., Kahle, J. B., Fensham, P., Lazarowitz, R., Rennie, L. J., Fraser, B., Staver, J. R., Gallard, A., Jimenez-Aleixandre, M. P., Dillon, J., Moscovici, H., Tuan, H-L., Emdin, C., Tobin, K., Roth, W-M. (2008). NARST: A lived history,*Cultural Studies of Science Education*, *3,*157–207.

Karplus, R. & Their, H.D. (1967). *A New Look at Elementary School Science*. Chicago: Rand McNally and Co.

Kilpatrick, J. (1992). A history of research in mathematics education. In *Handbook of research on mathematics teaching and learning*, D. A. Grouws, Ed., New York: Macmillan.

Kinsella, J.J. (1952). The problem of locating research studies in mathematics education. *Mathematics Teacher*, *45*, 273-275.

Kyle, W. C., Jr., Linn, M. C., Bitner, B. L., Mitchner, C. P., & Perry, B. The role of research in science teaching: An NSTA theme paper, *Science Education*, *75*(4), 413-418.

Lagowski, J. J. (1998). Chemical education: Past, present, and future. *Journal of Chemical Education*, *75*(4), 425-436.

McDermott, L. C. & Redish, E. F. (1999). Resource letter PER1: Resource letter on physics education research. *American Journal of Physics*, *67*, 755-767.

McKinnon, J.W, & Renner, J. W. (1971). Are colleges concerned with intellectual development? *American Journal of Physics, 39*, 1047-1052.

Moore R. J. & Schwenz R. W., (1992), The problem with physical chemistry, *Journal of Chemical Education*, **69**, 1001-1002.

Morton, R. L. (1953). *Teaching arithmetic* (What research says to the teacher, No. 2). Washington, DC: National Education Association.

Nakhleh M. B., (1993), Are our students conceptual thinkers or algorithmic problem solvers? *Journal of Chemical Education,* **71**, 52-55.

Nurrenbern, S. C. & Robinson, W. R. (1994). Quantitative research in chemical education. *Journal of Chemical Education*, *71*(3), 181-. Orgill, M. (2003). Playing with a double-edged sword: Analogies in biochemistry. Unpublished doctoral dissertation, Purdue University, West Lafayette, IN.

Orgill, M. & Bodner, G. M. (2004). What research tells us about using analogies to teach chemistry, *Chemical Education Research and Practice*, *5*(1), 15-33.

Orgill, M. & Bodner, G. M. (2006). An analysis of the effectiveness of analogy use in college-level biochemistry textbooks, *Journal of Research in Science Teaching*, *43*(12), 1040-1060.

Orgill, M. & Bodner, G. M. (2007). Locks and keys: How analogies are used and perceived by biochemistry students, *Biochemistry and Molecular Biology Education*, *35*, 244–254.

Patrick, W. A. (1924). What kind of research is essential to good teaching? *Journal of Chemical Education*, *1*(1), p. 16-17.

Phelps, A. J. (1994). Qualitative methodologies in chemical education research. *Journal of Chemical Education*, *71*(3), 191-.

Phelps A. J., (1996). Teaching to enhance problem solving: it's more than the numbers, *Journal of Chemical Education,* **73***,* 301-304.

Pribyl, J. R. & Bodner, G. M. (1987). Spatial ability and its role in organic chemistry: A study of four organic courses, *Journal of Research in Science Teaching*, *24*, 229-240.

Pribyl, J. R. (1994). Using surveys and questionnaires. *Journal of Chemical Education*, *71*(3), 196-.

Rainey, R. G. (1965). The effects of directed versus non-directed laboratory work on high-school chemistry achievement, *Journal of Research in Science Teaching*, *3*(4), 286-292.

Reed, R. D. (1929). The high-school teacher and research. *Journal of Chemical Education*, *6*(3), 564-565.

Resnick, L.B. (1983). Mathematics and science learning: A new conception. *Science*, *220*, 477-78.

Romberg, T. A. (1969). Current research in mathematics education. *Review of Educational Research*, *39*, 473-491.

Shymansky, J. A. & Kyle, W. C. (1992). Establishing a research agenda: Critical issues of science curriculum reform, *Journal of Research in Science Teaching*, *29*(8), 749-778.

Slavin, R. E. (2002). Evidence-based educational policies: Transforming educational practice and research. *Educational Researcher, 31*(7), 15-21.

Towns M. H. & Grant E. R., (1997). “I believe I will go out of this class actually knowing something”: cooperative learning activities in physical chemistry, *Journal of Research in Science Teaching*, **34**, 819-835.

Ward, C. R. & Herron, J. D. (1980). Helping students understand formal chemical concepts, *Journal of Research in Science Teaching*, *17*(5), 387-400.

Yarroch W. L., (1985), Students’ understanding of chemical equation balancing, *Journal of Research in Science Teaching*, **22***,* 449-459.

Zielinski T. J., (1995), Promoting higher-order thinking skills: uses of mathcad and classical chemical kinetics to foster student development, *Journal of Chemical Education*, **72**, 631-638.

Table 1. Ph.D. Dissertation Topics

Laboratory-based instruction

Designing general chemistry laboratory experiments that enhance cognitive development from a Piagetian perspective; the effect of structured writing on achievement, time and accuracy in the general chemistry laboratory; the efficacy of computer-assisted labs; what defines effective chemistry instruction in the laboratory; the students perspective of the chemistry teaching laboratory; the development and evaluation of a research-based undergraduate laboratory; the effect of authentic research experience and inquiry on teachers and students.

Teacher's understanding

Prospective elementary school teacher's understanding of the particulate nature of matter; how teacher's beliefs about science and science teaching shape their classroom instruction; high-school chemistry teachers' perceptions and actions; how science methods course can enrich the pedagogical content knowledge of prospective chemistry teachers; the professional development of graduate teaching assistants in chemistry; high-school science teachers' beliefs about the intended and actual impacts of standards-based reforms

Student's Understanding

Use of the learning cycle to promote cognitive development; students' perceptions of academic dishonesty in a chemistry classroom; assessment of the impact chemistry text and figures have on visually impaired students' learning; an investigation of students' degree of concept links as a function of exposure to college chemistry courses; a case study of a female pre-professional major's perspective of learning chemistry; case studies of concept maps from the perspectives of middle-school students; a phenomenographic study of the beliefs and practices of general chemistry students and faculty members regarding knowledge transfer: a phenomenographic study; ontological categorization in chemistry: a basis for conceptual change in chemistry; relating macroscopic observations of melting and mixing to microscopic explanations

Problem Solving

Problem solving behaviors of concrete and formal operational high school chemistry students when solving chemistry problems requiring Piagetian formal reasoning skills; investigation of variables involved in chemistry problem solving; implementing instruction to improve the problem-solving abilities of general chemistry students; the role of beliefs in general chemistry problem solving; the effect of interactive instruction and lectures on the achievements and attitudes of chemistry students; a comparison of low spatial ability students and high spatial ability students representation and problem solving processes on stoichiometry questions; the role of multiple representation systems in problem solving in chemistry; student's understanding of chemical equilibrium as revealed by algorithmic and conceptual problems; a phenomenographic analysis of how chemistry students study for an exam: a phenomenographic analysis; an investigation of the effective aspects of multiple external representations for students learning chemistry

Alternative Modes of Instruction

A comparison of student-directed and teacher-directed modes of instruction for presentation of density to high school chemistry students; an inquiry into what happens when the lecturer stops lecturing in organic chemistry courses; a longitudinal study of Action Research as the vehicle for curriculum change in analytical chemistry

Computer-based Instruction

The effect of drill question sequencing on learning and user satisfaction in computer-assisted instruction in molecular geometry; integrating the microcomputer into the high school chemistry classroom; an investigation of the relationship between student cognitive characteristics and the use of hypermedia science tutorials; an investigative look at the experiences of students using the computer in science classrooms; student participation in world wide web-based curriculum development of general chemistry; investigation of student use of web-based tutorial materials and understanding of chemistry concepts

Research in Advanced-Level Courses

A study of undergraduate and graduate students' conceptual understanding of thermodynamics; learning in quantum mechanics; how students use spectro-photometric instruments to create understanding; using spectral analysis to probe the continuum of problem solving ability among practicing organic chemists; the role of analogies in biochemistry; understanding arrow-pushing formalism from a student's perspective; a cognitive model of second-year organic chemistry students' conceptualizations of mental molecular rotation; how students learn to solve organic synthesis problems

Content-Based Research across Disciplines

A critical action research approach to curriculum development in a lab-based chemical engineering course; curricular reform in computer-based undergraduate laboratories via Action Research; an investigation of the factors involved in self-efficacy belief modification in the first-year engineering experience; students' conceptions and problem solving ability in a modeling-based interactive engagement in an introductory physics course; similarities and differences in design across disciplines