TÜRK FEN EĞİTİMİ DERGİSİ
Yıl 5, Sayı 2, Ağustos 2008

Journal of
TURKISH SCIENCE EDUCATION
Volume 5, Issue 2, August 2008

http://www.tused.org

Building a Structure for Doing Content-Based Education Research at the Tertiary Level

George M. Bodner[1], Faik Ö. Karataş[2], Anthony G. Rud[3]

[1] Prof. Dr., Department of Chemistry, College of Science, Purdue University, West Lafayette, IN 47907, USA
[2] Research Assist., Department of Curriculum & Instruction, College of Education, Purdue University, West Lafayette, IN 47907, USA
[3]Assoc. Prof. Dr., Department of Educational Studies, College of Education, Purdue University, West Lafayette, IN 47907, USA

Invited Paper

The original language of article is English (v.5, n.2, August 2008, pp.2-10)

ABSTRACT

It has been slightly more than 25 years since the Division of Chemical Education was established within the Department of Chemistry at Purdue University. This graduate program was created to promote content-based education research that focused on the particular problems of teaching and learning in chemistry. Another goal of this program is to increase the amount of research being done on the teaching and learning of chemistry in advanced-level undergraduate courses, such as organic and physical chemistry, or biochemistry. A similar approach has recently been adopted within the College of Engineering at Purdue through the creation of the first School of Engineering Education in the U.S. in order to facilitate rigorous education research that goes beyond the limits of traditional engineering education. We believe that content-based research such as the work being carried out in these programs provides one of the best ways to improve teaching and learning at the tertiary level in order to meet the needs of our global and local society. This paper therefore describes these two content-based education research programs at Purdue University in order to provide models for other institutions to apply as they think about ways to meet their nation's needs.

Keywords: Chemical Education, Engineering Education, Content-Based Educational Research, Tertiary Level (Higher Education)

INTRODUCTION

The National Association for Research in Science Teaching (NARST) was originally created to serve the needs of individuals involved in training science teachers (Joslin et al., 2008). When the organization was formed in 1928, it had 17 members concentrated in the northeast region of the United States; today NARST is an international organization of approximately 1000 members. From 1929 until the early 1960s, NARST was associated with a journal known as *Science Education*. According to Joslin et al., the eight major fields served by *Science Education* were "nature study and elementary science; junior high school science or general science; senior high biology, chemistry and physics; training science teachers; supervision of science instruction; and research in science education." In May, 1963, the first issue of the *Journal of Research in Science Teaching* was published by the leadership of NARST to increase the emphasis on research in science education. To this day, NARST describes it goals in terms of "investigations of teaching and learning in science" and "communicating science education research findings ...." (NARST, 2008).

The goal of this paper is to describe two general trends in education research that have occurred in recent years that have taken groups of researchers away from the traditional approach to research in science education fostered by NARST for so many years. The first involves a gradual shift from the search for general truths that are valid across the disciplines of science, technology, engineering and mathematics — the so-called STEM disciplines — toward content-based research that focuses on the problems faced by students and their instructors in an individual discipline, such as chemistry or physics. The second trend involves a shift from the search for general truths that primarily apply to elementary and secondary school students, or to students of all ages, toward an emphasis on the particular problems associated with teaching and learning at the college or university level. These trends represent a major change in the nature of education research that has implications for the structure of science education programs in the 21st century for many countries.

1- Content-Based Education Research at the Tertiary Level

Bodner and Weaver (2008) recently 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. As a result, they noted, this research focused on the problems faced by elementary and secondary school students when they were exposed to chemistry for the first time. In other words, as chemical education research began to separate itself from science education, in general, the focus of this research was still on the students for whom teacher training programs prepared instructors.

Over a period of about 25 years, however, 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 — either in large enrollment first-year courses or advanced level courses in biochemistry, organic chemistry, and physical chemistry, for example. As noted elsewhere (Bodner and Weaver, 2008), when one of us (GMB) first attended meetings of the National Association for Research in Science Teaching (NARST) or the American Educational Research Association (AERA) he found that papers that focused on the issues of teaching and learning at the tertiary level were rare. Today, a significant fraction of the papers at both meetings deal with the problems faced by faculty and students at the college or university level.

A major shift has recently begun in colleges of engineering in the U.S. that may be of interest to faculty involved in content-based educational research in other countries. This shift involves the development of engineering education research as a separate field of study. The magnitude of the change might be illustrated by noting that the *Journal of Engineering Education* was recently transformed after more than 90 years of existence "to serve as an archival record of scholarly research in engineering education" (Lohmann, 2003), rather than continuing to serve as a repository of articles that describe the "practice" of teaching applied to a particular course at a given institution. By taking this action, the *Journal of Engineering Education* became "the first journal in the engineering community dedicated solely to the publication of research in engineering education" (Lohmann, 2005). In much the same way that Purdue University took an active role in the development of chemical education research at the tertiary level, Purdue has demonstrated a growing commitment to research in engineering education through the creation of a new department that offers graduate degrees in engineering education (Haghighi, 2005).

Proponents of the emerging field of engineering education have raised the question: How do we help faculty and staff interested in improving engineering education shift their focus from the traditional issues of classroom *teaching* toward fundamental research-based questions about how engineering students *learn*? (Wulf, 2002; Grimson, 2002; Streveller & Smith, 2006). This is an interesting question, by itself. But it brings to mind two hidden assumptions. First, that traditional work in engineering education did not meet the requirements of rigorous, so-called scientific, research. Second, that there is, in fact, a need to conduct rigorous research in engineering education. This paper will attempt to discuss these hidden assumptions and compare the development of a research-based approach to engineering education to developments in chemical education that occurred more than two decades ago (Bodner & Herron, 1984). Our goal is to provide a model that might be useful for content-based education research programs in other countries as they expand their research base to meet the needs of faculty and staff who teach at the college and university level.

2- Establishing a Basis for Doing Content-Based Research on Teaching and Learning

The creation of the Division of Chemical Education at Purdue, which occurred in 1982, was described in an article by Bodner and Herron (1984) that appeared in the *Journal of College Science Teaching*. They 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)

Until recently, a similar situation could be found in colleges of engineering. With a few noteworthy exceptions, most of the individuals contributing to engineering education were faculty whose primary responsibilities were administering large programs within individual departments or whole colleges, or carrying out traditional research within one of the content areas within the field of engineering.

Bodner and Herron (1984) argued that the term *chemical educator* had evolved over the years. They noted that it was originally 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." Roughly 25 years ago, they noted "... 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." Changes such as those that recently took place in the editorial policy of the *Journal of Engineering Education* and the administrative structure of the

College of Engineering at Purdue University suggest a similar evolution in the term *engineering educator*.

In much the same way that creation of the Division of Chemical Education at Purdue led to the first large-scale graduate program in chemical education in the U.S., Purdue recently created a Department of Engineering Education within the College of Engineering (Haghighi, 2005). The new Department of Engineering Education was given status equal to that of traditional programs in disciplines such as chemical or mechanical engineering and new programs in emerging disciplines such as biomedical engineering.

When discussions of the creation of a graduate program in engineering education began, there were four faculty at Purdue whose primary interests were in research-based engineering education. By the beginning of the Fall semester of the 2007-2008 academic year, there were 24 faculty with a full-time, part-time or courtesy appointment in engineering education. It is interesting to note that one of these individuals is the Dean of the College of Engineering. At the time this paper was written, 20 students were working toward graduate degrees in this new program.

3- Examples of Content-Based Education Research

The Division of Chemical Education at Purdue evolved out of collaboration between faculty educated in the tradition of science education research and faculty from a department of chemistry involved in teaching large-enrollment classes at the undergraduate level to both chemistry majors and non-majors. In the years before the chemical education research program was created at Purdue, dissertation research topics supervised by faculty who eventually became members of this program included studies of the effect of pairing and pacing on the rate at which learning occurred among 7th-grade students enrolled in an Intermediate Science Curriculum Study (ISCS) course (Gabel, 1974), and concrete-formal Piagetian stages and science concept attainment (Cantu-Salinas, 1977). In other words, dissertation topics before the program was created were examples of classical science education research.

Examples of content-based education research done by students who have graduated from the Division of Chemical Education since it was formed more than 25 years ago include studies of the unique features of problem solving in chemistry, such as the relationship between spatial ability and achievement in organic chemistry courses (Pribyl, 1984), the roles of beliefs in general chemistry problem solving (Carter, 1987), and the role of multiple representation systems in problem solving in chemistry (Domin, 1993).

Whereas traditional science education research has examined the meaning of the concepts of heat and temperature among elementary and secondary school students, content-based education research at Purdue within the domain of physical chemistry has probed the conceptual understanding of thermodynamics by undergraduate and graduate students (Patron, 1997) and the way undergraduates approach the learning of quantum mechanics (Gardner, 2002). Over a period of years, multiple studies have also been done within the context of undergraduates and graduate students enrolled in organic chemistry classes, including studies of the arrow-pushing formalism from a student's perspective (Ferguson, 2003), problem-solving within the context of combined spectral analysis problems encountered by practicing organic chemists (Cartrette, 2003), subconscious cognitive processes used by second-year organic chemistry students during the mental rotation of molecular structures (Briggs, 2004), and so on.

The evolution of the Department of Engineering Education at Purdue (Haghighi, 2005) had one feature in common with the Division of Chemical Education: Both programs were created by appropriate administrators as a result of proposals submitted to them by faculty in the appropriate departments. The primary difference between the origin of the two programs was the fact that the chemical education program grew out of an established science education research collaboration, whereas the engineering education program did not.

4- Need for rigorous research

The call for "rigorous research" in science and engineering education should not be interpreted as a return to the paradigm wars of the 1980s (Gage, 1989), which were described by Bodner (2004) as a period "... during which proponents of the traditional, quantitative, experimental or quasi-experimental paradigm fought pitched battles with advocates of a naturalistic, qualitative approach to research." Rigorous research can employ either qualitative, quantitative, or mixed methods of inquiry, but it must be done in a valid, reliable, and credible way (McMillan & Schumacher, 2001; Patton, 2002; Shavelson & Towne, 2002). The study must be firmly based on well-crafted research questions that are consistent with both the methodology used to determine how data are collected and the theoretical framework upon which the study is based (Bodner and Orgill, 2007) and should lead to results that can provide the basis upon which the science and engineering education community can think about the way they teach their courses (Shavelson & Towne, 2002). Rigorous research should help achieve the purpose of educational research defined as Borg and Gall (1983), which is to develop new knowledge about teaching, learning and, perhaps even administration, in order to improve educational practice both within and outside the classroom.

The obvious success of the science and engineering enterprise in the second-half of the 20th century might lead some to question the need for revolutionary changes in the way scientists and engineers are educated. It can be argued, however, that a variety of factors that have arisen in the recent years mandates a new approach to the education of scientists and engineers. One of these factors is a direct result of the success of the previous generation of scientists and engineers, which has resulted in a significant increase in the complexity of the problems the next generation of scientists and engineers are expected to solve (Wulf, 2002). A second factor is the increase in the rate at which scientific discoveries and engineering innovations are being implemented due to the new opportunities for fast response to problems provided by a global workforce. Science and engineering have also become increasingly interdisciplinary, multidisciplinary fields because of the complexity of contemporary problems (Creed et al., 2002; Suman et al., 2002; Felder et al., 2005). In a recent address to the National Academy of Engineering, the president of that organization discussed how the constraints of engineering design are getting more complex by comparing his experiences in engineering with his father's.

> My Dad was a mechanical engineer, ... [whose] constraints were mostly functionality and cost. It was pretty simple. The lowest cost design to achieve certain functionality was it. ... now we have safety, reliability, manufacturability, reparability, maintainability, and ecological considerations … Some of the constraints that we work with are not easily measured and trade-offs are not easily allowed. (Wulf, 2002, p.5)

Other challenges that the graduates of our science and engineering programs will face include the rate of growth of knowledge, the need to diversify the field to include women and minorities, the need for a strong life-long learning program for all scientists and engineers, as well as retention issues in science and engineering programs (Fortenberry 2006; Fromm 2003; Guest 2006; Shuman *et al* 2002; Wulf 2002). A recent National Academy of Engineering report (The Engineer of 2020: Visions of Engineering in the New Century, 2004) noted that engineers in 2020 will need to remain well-grounded in the basis of mathematics and science, but they will need to expand their vision of design through a solid grounding in the humanities, social sciences, and economics. This is consistent with the increased emphasis on humanities, social science and economics in engineering design that is part of the ABET standards (ABET, 2000) used to accredit engineering education programs.

Whereas traditional science and engineering education programs produced graduates with the necessary technical knowledge, scientists and engineers who will be competitive in today's workplace must also be effective communicators, team players, and understand the non-technical and human factors that affect engineering design (ABET, 2000). They will have to be able to work in interdisciplinary teams to serve a globally diverse customer base (Shuman et al, 2002; Fromm, 2003; Fortenberry, 2006; Wormley, 2006). As industry shifts from large companies producing inexpensive commodities for the global market to small companies that produce innovative, customer-oriented, "branded" products, it is increasingly important for scientists and engineers to possess other skills, such as entrepreneurship (Creed et al., 2002; Becker 2006).

Engineering education for the last half century has focused on producing graduates who are technically competent and who have a deep understanding of the scientific and mathematical principles underpinning their particular discipline (Reynolds & Seely, 1993). This focus on an "engineering science" approach was developed in the United States following World War II and resulted in a substantial increase in the scientific and mathematical content of engineering curricula, with a corresponding decrease in the amount of time students spent on laboratory work and on more specialized professional engineering education. This science-based approach to engineering education is increasingly being questioned and criticized, however, both by the profession in general and by engineering educators (Grimson, 2002) because engineers need a variety of skills and perspectives beyond the traditional basic science and technical background in order to be successful.

Some might argue that the need for fundamental changes in the approach taken to the education of the next generation of scientists and engineers does not automatically translate into a call for rigorous research in science and engineering education. They might argue that all we need is to continue curriculum development along the lines of the traditional articles that were published for so many years in the journals such as the *Journal of Engineering Education*. They might argue that fundamental research on teaching and learning that has been done in the fields of educational psychology, science education, and mathematics education should have provided the critical information upon which new approaches to engineering education can be based. We would like to suggest that the history of efforts to bring a strong research tradition into chemical education can provide evidence that bringing the results of research from other fields into engineering may be both necessary and useful, but cannot be sufficient to solve the problems engineering educators face.

Research in chemical education has demonstrated the existence of content-specific challenges to teaching and learning that are not necessarily shared by other branches of science and mathematics. Examples of this can be found in the literature on problem solving in chemistry (Bodner & Herron, 2002), organic synthesis (Bhattacharyya & Bodner, 2005), and quantum mechanics (Gardner & Bodner, 2007), for example. There is reason to expect a similar phenomenon in engineering education because the practice of engineering is fundamentally different from that of science and mathematics.

The core of engineering practice is "design" and what engineers do is "design under constraints" (Wulf, 2002). Design requires more of an emphasis on synthesis than analysis, although analysis still plays an important role in engineering science. Science and mathematics education in recent years has focused on conceptual understanding, application and analysis, but not on synthesis. In traditional approaches to science education, questions are asked about existing relations, and experiments are conducted to understand and analyze different phenomena or concepts. Science education teaches students to probe the “causes and effects” upon which the world in which we live is based, but seldom goes beyond that. Although engineering is similar to science, in some ways, it is also distinct because of the emphasis on design, which often makes engineering look more like architecture or art.

If, as we have argued, the activities of the members of the community of practice known as engineering are different from those in science and mathematics, students will need to be introduced to the field in a different way. Rigorous research is going to need to be done to help us understand how to develop the skills necessary to help engineers invent and innovate through design, rather than discovery as practiced by scientists.

CONCLUSION

There is a general consensus among leaders in the STEM disciplines that recent developments in engineering and science have changed the nature of the practice of both fields. There is also a general consensus among engineering educators that current engineering graduates are not being prepared for this new way of doing engineering, and there is reason to believe that the same can be said about the current approach to training scientists.

Groups such as the National Academy of Engineers and the participants in the recent engineering education research colloquies (National Engineering Education Research Colloquies, 2006) have called for the reform of engineering education. Much has been said by groups representing the National Research Council that a similar problem exists in the education of scientists. The reform being called for has to go deeper than just changing the content of what is taught, because it has been estimated that the half-life of science and engineering knowledge is about five years. Wulf (2002), for example, has argued that the content of engineering courses in some fields is obsolete by the time the students graduate. In order to keep up with the pace of change in industry and the world, we need to transform the way science and engineering are taught at the college and university level. As a first step, we need to start recruiting science and engineering education research scholars who are familiar with the content of their fields of science and engineering and help them learn how to conduct rigorous research on all aspects of the teaching and learning of science and engineering. The result, a self-perpetuating discipline of science and engineering education, will be fruitful for the industrial sector, our society, and all humanity. We believe that the steps taken in chemical education and engineering education at Purdue provide useful models for individuals interested in fostering the content-based education research needed to improve science and engineering education in the 21st century.

REFERENCES

ABET Criteria 2000, Accreditation Board for Engineering and Technology, Baltimore, MD, http://www.abet.ba.md.gov.

Becker, F. S. (2006). Globalization, curricula reform and the consequences for engineers working in an international company, *European Journal of Engineering Education*, 31, 261-272.

Bhattacharyya, G., & Bodner, G. M. (2005). It gets me to the product: How students propose organic mechanisms. *Journal of Chemical Education*, *82*(9), 1402-1407.

Bodner, G. M., & Herron, J. D. (1984). Completing the Program with a Division of Chemical Education, *Journal of College Science Teaching*, 14, 179-180.

Bodner, G. M., & Herron, J. D. (2002). Problem Solving in Chemistry, in *Chemical Education: Research-Based Practice*, J. K. Gilbert, Ed., Kluwer Academic Publishers.

Bodner, G. M. (2004). Twenty years of learning how to do research in chemical education, *Journal of Chemical Education*, *81*, 618-628.

Bodner, G. M., & Ogill, M. (2007). *Theoretical Frameworks for Research in Chemistry/-Science Education*, Upper Saddle River, NJL Prentice Hall.

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

Borg, W. R. & Gall, M. D. (1983). *Educational research: An introduction* (4th ed.). New York: Longman.

Briggs, M. (2004). *Second-year organic chemistry students' conceptualizations of mental molecular rotation*. Unpublished doctoral dissertation, Purdue University.

Cantu-Salinas, L. (1977). *Concrete-formal Piagetian stages, field independent-field dependent cognitive style, and science concept attainment.* Unpublished doctoral dissertation, Purdue University.

Carter, C. S. (1987). *The role of beliefs in general chemistry problem solving.* Unpublished doctoral dissertation, Purdue University.

Cartrette, D. (2003). *Using combined spectral analysis to probe the continuum of problem solving ability*, Unpublished doctoral dissertation, Purdue University.

Creed, C. J., Suuberg, E. M. & Crawford, P. G. (2002). Engineering entrepreneurship: An example of a paradigm shift in engineering education, *Journal of Engineering Education,* 91, 185-194.

Domin, D. S. (1993). *The role of multiple representation systems in problem solving in chemistry*, Unpublished doctoral dissertation, Purdue University.

Felder, R. M., Shephard, S. D. & Smith, K. A. (2005). A new journal for a field in transition, *Journal of Engineering Education*, 94, 7-10.

Ferguson, R. (2003). *Understanding arrow-pushing formalism from a student's perspective*, Unpublished doctoral dissertation, Purdue University.

Fortenberry, N. L. (2006). An extensive agenda for engineering education research, *Journal of Engineering Education*, 95, 3-5.

Fromm, E. (2003). The changing engineering educational paradigm, *Journal of Engineering Education*, 92, 113-121.

Gabel, D. (1974). *The effect of pairing and pacing on learning rate in ISCS classrooms*, Unpublished doctoral dissertation, Purdue University.

Gage, N. (1989). The paradigm wars and their aftermath: A "historical" sketch of teaching science., *Educational Researcher*, *18*(7), 4-10.

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

Gardner, D. E., & Bodner, G. M. (2007). Existence of a Problem-Solving Mind set among students taking quantum mechanics and its implications. In *Advances in Teaching Physical Chemistry*, M. D. Ellison and T. A. Schoolcraft, Ed., Washington, DC: American Chemical Society.

Grimson, J. (2002). Re-engineering the curriculum for the 21st century. *European Journal of Engineering Education*, 27, 31-37.

Guest, G. (2006). Lifelong learning for engineers: A global perspective, *European Journal of Engineering Education*, 31, 273-281.

Haghighi, K. (2005). Quiet no longer: Birth of a new discipline. *Journal of Engineering Education*, *95*(4), 351-353.

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.

Lohmann, J. R. (2003). Mission, Measures, and Manuscript Central (TM), *Journal of Engineering Education*, *92*, 1.

Lohmann, J. R. (2005). Building a community of scholars: The role of the Journal of Engineering Education as a research journal, *Journal of Engineering Education*, *94*, 1-3.

McMillan, J. H. & Schumacher, S. (2001). *Research in education: A conceptual introduction* (5th ed.). New York: Addison Wesley Longman, Inc.

NARST (2008). From the NARST website http://www.narst.org/about/mission.cfm, last accessed 23 May 2008.

National Academy of Engineering, The engineer of 2020: Visions of engineering in the new century, Washington, DC: The National Academies Press, 2004.

National Engineering Education Research Colloquies. (2006). *Journal of Engineering Education*, *95*, 257-261.

Patron, F. (1997). *Conceptual understanding of thermodynamics: a study of undergraduate and graduate students,* Unpublished doctoral dissertation, Purdue University.

Patton, M. Q. (2002). *Qualitative research & evaluation methods* (3rd ed.). California: Sage Publication.

Pribyl, J. (1988). *A Comparison of Low Spatial Ability Students and High Spatial Ability Students Representation and Problem Solving Processes on Stoichiometry Questions*, Unpublished doctoral dissertation, Purdue University.

Reynolds, T., & Seely, B. (1993). Striving for balance: A hundred years of the American Society for Engineering Education. Journal of Engineering Education, 82(3), 136-151.

Shavelson, R. J., & Towne, L. (2002). *Scientific research in education*. Washington, DC: National Academy Press.

Streveller, R. A. & Smith, K. A. (2006). Conducting rigorous research in engineering education, *Journal of Engineering Education*, 95, 103-105.

Wormley, D. N. (2006). A year of dialogue focused on engineering education research, *Journal of Engineering Education*, 95, 179.

Wulf, W. A. (2002). The urgency of engineering education reform, *Journal of Science, Technology, Engineering, and Mathematics Education*, 3 (July-December), 3-9.