AN EDUCATIONAL RESEARCH AGENDA FOR SMET HIGHER EDUCATION

Norman L. Fortenberry
Director, Division of Undergraduate Education
National Science Foundation*

Abstract

This paper identifies the National Science Foundation as the major sponsor of educational research in science, mathematics, engineering, and technology education. It identifies key questions which constitute the basis for an educational research agenda. Gaps in the pursuit of that agenda within engineering education are identified by examination of articles published in the *Journal of Engineering Education* over the past six years. Finally, a model of a coherent research process for engineering education is offered from an example drawn physics education.

I. Introduction

Major support for educational research is provided by several private and public and private sources. The Spencer Foundation provides support for educational research projects in the range of $300,000 - $400,000 per year for 3 to 4 years. In fiscal 1998, the Spencer Foundation supported 30 projects[1]. The James S. McDonnell Foundation supports Cognitive Studies for Educational Practice; since 1987 the Foundation has expended $25 million in support of educational research and training[2]. The Department of Education's (ED's) Office of Educational Research and Improvement, under its Field Initiated Studies competition, made 30 awards totaling over $5 million in fiscal year 1997[3]. The National Science Foundation's (NSF's) Division of Research, Evaluation, and Communication invested over $25 million in support of educational research projects in 1997 alone, and invested an additional $30 million in educational technologies and evaluation activities. Not included in these totals are funds invested by other operating divisions (e.g., Division of Undergraduate Education, Division of Engineering Education and Centers, and Division of Social, Behavioral, and Economic Research) and certain NSF-wide initiatives which include significant elements contributing to educational research (e.g., Learning and Intelligent Systems). Thus, NSF is the dominant player in this arena. Within the indicated group of funders, NSF alone focuses exclusively on science and engineering education.

NSF has had programs supporting educational research since, at least, 1980. However, much of the research undertaken was on mathematics learning at the elementary level, with some work on science learning, and some work also on the role of instructional technologies. Much less

* The views expressed are those of the author and do not necessarily represent the policies and opinions of the Division of Undergraduate Education or the National Science Foundation.

work was done on mathematics and science instruction at the pre-college level, and very little research, in any SMET discipline, was supported at the undergraduate and graduate levels.

In fiscal year 1997, NSF initiated the Research and Educational Policy and Practice (REPP) program, a broader effort to enhance the quality and impact of the Nation's SMET education by building a knowledge base of ideas, practices, and policy alternatives to strengthen the research base and build a foundation to advance educational practices from classroom to state-wide levels[4]. In addition to research on teaching and learning, REPP incorporates elements of the previous portfolio in support of educational technologies. However, the predominant focus has remained on activities at the pre-college level.

The 1995 NSF Strategic Plan identifies integration of research and education as a core strategy[5]. One result of this rising interest in integration of research and education has been increased emphasis on activities at the undergraduate level which is at the nexus for activities across the educational continuum—receiving students from the K-12 sector and returning teachers to that sector, and preparing students for graduate study while also receiving doctoral graduates as new faculty. This increased attention to the undergraduate sector motivates discussion of the types of educational research that can best advance teaching and learning at this level and within higher education in general.

II. Framework

NSF supports the development and dissemination of educational best practices, not sustained operations. Thus, it's portfolio of projects should provide the means to answer meta-level questions on best practices. Individual supported projects should answer aspects of those broader questions.

The most fundamental educational research is on cognitive science. This research is conducted by The National Institute for Child Health and Development, the Office of Naval Research, and NSF[6]. Indeed, NSF has just announced a joint initiative which links, NSF, ED, and The National Institute of Child Health and Development[7]. The next level of research is theory development, followed by theory testing accomplished by comparative trials (existing population to previous populations, pre-test and post-test on the same population, and matched random samples of "test" and "control" populations).

I suggest that there are at least two (see endnote for a possible third) categories within which to examine the research to be conducted. The first category is fundamental research. This includes research on teaching, learning, applications of educational technology, assessment, and discipline-specific aspects of the preceding list. The other category is research applied in direct support of implementation activities. This category includes research on educational systems and how to make them more effective, scaling up effective practices from prototype to full-scale implementation, and institutionalization.

A. Fundamental Research

I believe that five broad areas particularly require illumination under the rubric of fundamental research. These include the following:

1. What are the critical factors, optimal environments, necessary boundary conditions, and resultant indicators for effective instruction within the various SMET disciplines?

2. What are the social, cultural, and institutional factors which affect participation in SMET fields by individuals and demographic groups; and how are they mitigated or optimized?

3. What are the effects of teaching and learning technologies on instruction, student learning, and student critical thinking?

4. What are the indicators of success and attainment in SMET education and how are these correlated with input and output measures?

5. What new pedagogic theories and techniques might be effectively employed within SMET disciplines?

Although these areas are rather broad they do have practical uses. For example, judgments of the effectiveness of a given curricular approach is embedded in area 1.

B. Applied Research

Similarly, I would identify five broad areas requiring illumination under a program of applied research. These are the following:

1. How is transference of pedagogic and instructional innovations between SMET disciplines best achieved?

2. How is systemic reform best initiated, scaled-up, and institutionalized within higher education?

3. How are institutional and disciplinary (i.e., those things "controlled" by the departments, professional societies, and professional networks) policies and procedures most effectively modified in support of enhanced student learning?

4. How do we best facilitate the transitions between educational levels and between academe and the workplace?

5. How are specific pedagogic theories and techniques best instituted within a given context?

In this context applied research normally involves study of educational programs which themselves constitute "implementation research," that is, an attempt to deduce general lessons from the analysis of a particular programmatic implementation. Questions that researchers seek to answer during such implementation research include the following[8]:

1. What theory of instructional improvement underlies the design?
2. How good is the evidence?
3. Are effects sustained?
4. Have the effects been disaggregated?
5. How long does it take to produce positive results?
6. Under what conditions has the project/program produced positive results?
7. Are there important prerequisite conditions for obtaining good results?
8. What are the initial and recurring costs?
9. How well specified is the program?
10. What support is provided and how good is it likely to be?
11. Will local capacity to support the designs be developed?
12. Does the program fit well with previous local investments in institutional improvement?
13. Is the program complete?
14. What are the opportunity costs?
15. What is the provider willing to be accountable for?
16. Is the model proven, promising, or at least plausible?

III. Educational Research Agenda for SMET Higher Education

While the research areas identified above have salience at all educational levels, they take on particular significance in higher education because so little previous work has been done which focuses on this sector. So that both fundamental and applied research are addressed, it would be optimal if an overarching research program combined theory development with empirical validation. Such a program could improve SMET learning in higher education by identifying and providing the basis for infusion into widespread implementation of effective instructional strategies, learning environments, and institutional practices.

An expanded taxonomy of the fundamental and applied research issues areas within the context of higher education is shown in Appendix A.

IV. Activities to Date in Engineering

Although many journals exist to report on educational research (see Appendix B), it is, perhaps, most appropriate for this audience to restrict discussion to the *Journal of Engineering Education*. The revamped *Journal of Engineering Education* debuted in January 1993. A key feature of the revised journal's editorial policy is a commitment to rigorous peer review and publication of high quality scholarly articles[9]. Examination of the past six years of the *Journal* provides an informative overview of the current state of educational research in engineering education. This approach is similar to that used by Wankat in which he found that only 13.4 percent of the articles published in the five years between 1993 and 1997 cited a specific educational theory[10].

Two hundred fifteen papers (excluding educational briefs) in nineteen issues published between January 1993 and January 1999 were examined (not including 6 issues published during this period) for their conformance to the taxonomy indicated above as shown in Table 1. Multiple counting was allowed for papers which appeared to cross multiple categories. The column labeled "Other" reflects articles which did not fit any of the other categories (for example an article on distribution of degrees, faculty, and funding among various engineering disciplines or another article defining the characteristics of an engineer).

Table 1. Classification of Articles appearing in various issues of the *Journal of Engineering Education.*

Issue	Articles per Issue	Number of Articles Addressing Various Research Issues			
		Fundamental	**Applied**	**Implementation**	**Other**
Vol 82, No 1	11	6	1	5	0
Vol 82, No 2	10	5	1	5	0
Vol 82, No 3	9	4	4	3	0
Vol 82, No 4	7	4	2	1	0
Vol 83, No 1	9	3	7	0	0
Vol 83, No 2	14	3	1	10	0
Vol 83, No 3	14	8	3	6	0
Vol 83, No 4	12	7	3	9	0
Vol 84, No 1	14	8	5	6	0
Vol 84, No 2	12	4	5	5	0
Vol 85, No 1	13	7	6	3	1
Vol 85, No 2	10	7	5	0	1
Vol 85, No 4	10	1	5	1	4
Vol 86, No 3	12	6	5	1	0
Vol 86, No 4	8	3	2	2	1
Vol 87, No 1	10	6	3	3	1
Vol 87, No 2	11	5	8	0	0
Vol 87, No 4	17	10	8	0	2
Vol 87, No 5	12	4	7	5	0
TOTAL	**215**	**101**	**81**	**65**	**10**

Numbers of articles addressing various issues exceed number of total articles due to multiple counting.

Table 2. Frequency Analysis of Types of Fundamental Research (FR) Questions Addressed by Articles Indicated in Table 1.

	No.	%FR	%Tot.
1. What are the critical factors, optimal environments, necessary boundary conditions, and resultant indicators for effective instruction within the various SMET disciplines?	33	30%	15%
2. What are the social, cultural, and institutional factors which affect participation in SMET fields by individuals and demographic groups; and how are they mitigated or optimized?	29	27%	14%
3. What are the effects of teaching and learning technologies on instruction, student learning, and student critical thinking?	20	18%	9%
4. What are the indicators of success and attainment in SMET education and how are these correlated with input and output measures?	15	14%	7%
5. What new pedagogic theories and techniques might be effectively employed within SMET disciplines?	12	11%	6%
TOTAL	109	100 %	51%

Number (109) of articles addressing specific fundamental research questions exceeds total number (101) articles addressing fundamental research questions overall because of multiple counting.

Table 3. Frequency Analysis of Types of Applied Research (AR) Questions Addressed by Articles Indicated in Table 1.

	No.	%AR	%Tot.
1. How is transference of pedagogic and instructional innovations between SMET disciplines best achieved?	0	0%	0%
2. How is systemic reform best initiated, scaled-up, and institutionalized within higher education?	7	8%	3%
3. How are institutional and disciplinary (i.e., those things "controlled" by the departments, professional societies, and professional networks) policies and procedures most effectively modified in support of enhanced student learning?	36	40%	17%
4. How do we best facilitate the transitions between educational levels and between academe and the workplace?	20	23%	9%
5. How best are specific pedagogic theories and techniques instituted within a given context?	26	29%	12%
TOTAL	89	100 %	41%

Number (89) of articles addressing specific applied research questions exceeds total number (81) of articles addressing applied research questions overall because of multiple counting.

It should be noted that the first column in Tables 2 and 3 are repetitions of the fundamental and applied research questions identified earlier. The second column in each table indicates the number of articles summarized in Table 1 which address the particular question. The third column represents the number in column 2 as a percentage of the total number of articles addressing the fundamental or applied research questions. The fourth column represents the number in column 2 as a percentage of all two hundred fifteen articles examined.

While another examiner might reach different conclusions as to the specific categorization of papers within the *Journal*, if the categorizations shown in Tables 1-3 is assumed reasonable, then several observations can be made. Comparing Tables 2 and 3, it's clear that the majority of articles are addressing fundamental questions and relatively fewer are addressing issues of application. Examining Table 2 in detail, one is struck by the scant attention given to the development of new pedagogic techniques. This may indicate an understandable tendency within engineering faculty to apply what knowledge is known rather than seeking to develop new knowledge in this area. More surprising, given the ABET 2000 emphasis on outcomes assessment, is a similar paucity of work correlating indicators of success and attainment with input and outcome measures. However, turning our attention to Table 3, this is somewhat balanced by noting the heavy emphasis given to changes in institutional or disciplinary policies and procedures. Overall, a certain insularity is observable within engineering colleges as reflected in the lack of attention given to systemic reform (surprising given the premise of the engineering coalitions), and the complete lack of explicit adaptation of innovations from other disciplines.

V. Future High Leverage Priorities in Engineering Education Research

The last point made, may provide an indication of how engineering education can identify high leverage priorities for the future. For example, there may be value in emulating the physics education research community (e.g, basic research on what it means to learn physics, development of assessment instruments, implementation of modified teaching strategies based upon research findings). A recent paper[11] in *Physics Today* traces the twenty year progress of the physics community in seeking the answers to three questions: 1) What is involved in understanding physics; 2) what do students bring to the physics classroom; and, 3) how do students respond to what they are taught? One reference[12] within this paper might be particularly interesting. It details research on student conceptual understanding of various topical areas, development and validation of assessment instruments, identification and analysis of student difficulties, development and assessment of instructional strategies, and development of instructional materials which incorporate research results. These physics references principally focus on fundamental research questions 1, 4, and 5 as well as applied research question 5 as defined in this paper. However, it seems to me that the greatest leverage would be obtained by developing an engineering framework for engineering education and pursuing the characterization of the elements of that framework. Two papers that lay the foundation for different approaches toward this end have appeared within the *Journal of Engineering Education*. The first[13] draws parallels between learning theories and product development. The second[14] suggests using systems engineering and quality control to influence instructional outcomes.

VI. NSF's Future Plans

NSF will support fundamental and applied research through a defined program which will supersede the REPP program. For example, NSF's Division of Research, Evaluation, and Communication has supported fundamental research on efficacy of small group learning by the National Institute of Science Education. That research has demonstrated a significant improvement in student learning[15]. The same division supported applied research on improving the efficacy of problem solving in engineering design classes[16].

Implementation research will result from analysis of projects supported through NSF's implementation programs at the pre-college (e.g., Teacher Enhancement Program), undergraduate (e.g., Course, Curriculum, and Laboratory Improvement Program), and graduate (Integrated Graduate Education and Research Traineeships Program) levels. For example, DUE supports adaptation and implementation of a variety of curricular and instructional innovations via the CCLI program. Based on the lessons learned as a result of individual grants, general lessons will be derived (e.g., the applicability of interactive lecture techniques to a variety of institutional settings).

Endnote

A third category might be infrastructure issues which, while not determining the research to be conducted, are contributing factors toward the decisions made. For example, there is a need to consider how we best produce the next generation of educational researchers in SMET disciplines, and how we best structure programmatic activities in support of enhanced teaching and learning at the undergraduate level. It would be optimal if programs of research were undertaken so as to provide maximal development of this community. One strategy would be to pursue research support coupled with graduate student traineeships. Another strategy would be to provide opportunities for those few SMET faculty currently engaged in educational research to mentor other interested SMET faculty in the conduct of such research. A model for this type of mentoring is given by the Research Sites for Educators in Chemistry program[17]. Thus, an important consideration for funders is the mix of support opportunities.

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NORMAN L. FORTENBERRY
Norman L. Fortenberry is Director of the NSF Division of Undergraduate Education. He is on leave from his position as clinical associate professor in the Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics at the Rensselaer Polytechnic Institute. He received the S.B., S.M., and Sc.D. degrees, all in mechanical engineering, from the Massachusetts Institute of Technology.

Appendix A. Taxonomy of Research Issues in Higher Education

I. FUNDAMENTAL RESEARCH

A. Knowledge base of teaching and learning within SMET disciplines

1. How can the evolving content of SMET disciplines be best communicated in various settings of interest?

2. How does systemic reform of SMET education become initiated and scaled up at both the undergraduate and graduate levels?

3. What is the delineation of the progression from basic skills to higher order thinking for key concept development within each SMET discipline?

4. What are the effects and significance of experiential learning (laboratory experiences, field experiences, etc.) on the learning process?

5. What are the relative advantages to undergraduate and graduate students of interdisciplinary programs? Do interdisciplinary programs sacrifice depth for breadth and what are the effects of any such trade-off? What is the prevalence and effectiveness of degree programs aimed less at preparation for graduate research and more at preparation for professional practice?

6. What knowledge, skills, and abilities provide the most useful foundation for life-long learning, problem solving, and adaptability?

7. What are robust means of authentic assessment of instructional effectiveness and student learning?

8. What assessment methods enhance student learning?

9. How can the education of under-prepared students be accelerated (individually and collectively)?

10. How is a more powerful culture of teaching created?

11. What is the relationship between a faculty member's subject knowledge and competence and his or her effective performance in the classroom?

12. What types of knowledge and abilities must instructors develop when it is no longer possible to be an "expert" in every area of student inquiry?

B. Research on Human Learning Applied to SMET disciplines

1. How do students interpret and process information in classrooms and laboratories?

2. How does student learning depend on context, demographic characteristics (age, gender, geographic region, socio-economic status, ethnicity, etc.), learning styles, and situational factors?

3. How do various teaching and learning modes (e.g., collaborative learning, constructivism, interdisciplinary or systems approaches, etc.) affect acquisition, retention, and transfer of learning in SMET areas of study?

4. How can simultaneous instruction of multiple individuals be tailored to each student's initial level of knowledge, thereby remediating those students with knowledge deficits?

5. Which specific learning experiences enhance critical thinking skills?

C. Research on the social, cultural, institutional factors affecting participation in SMET fields.

1. What types of students are attracted to SMET fields, under what conditions, or in anticipation of what outcomes?

2. What factors affect access, participation, persistence, and success of various demographic populations in undergraduate and graduate programs?

3. Which mechanisms of undergraduate and graduate student financial support are most effective for attaining different goals--providing effective mentoring experiences, providing independence and flexibility, encouraging shortest time to degree, encouraging interdisciplinary work?

4. What constitutes effective mentoring and/or career counseling, and does this differ for different fields or groups of students? Do students and faculty agree? Who is best prepared to provide this service--faculty, professional societies, individuals in the private sector, business consortia?

4. What are student attitudes towards science careers (including being a technician or K-12 teacher)?

5. What promotes non-SMET majors' willingness to acquire scientific and numeric literacy?

6. How do faculty attitudes affect their effectiveness in teaching?

7. What are faculty attitudes towards students, teaching, and various modes of teaching?

8. How does institutional mission affect receptivity to various student "types."

D. Research on the Effect of Various Teaching and Learning Technologies on how students think and learn as well as approach and solve problems with respect to changes in

1. time and location of learning (e.g., distance education by satellite, WWW, etc.)

2. rate of learning (e.g., self-paced systems)

3. temporal or conceptual access to process which are too fast, too slow, too large, too small too complex, or too dangerous to be normally accessed (e.g., use of simulations, visualizations, and various forms of instrumentation)

E. Research on Higher Education Systems

1. What are indicators of success in SMET fields; and how are those indicators correlated with input and outcome measures?

2. What are the factors affecting participation rates, retention, and successful attainment?

3. Which metrics can provide effective baseline measures of students' initial knowledge of SMET areas; can these metrics be applied to show value added from individual courses, blocks of courses, or entire curricula?

4. Which metrics are most effective for evaluating institutional commitment to educational reform as a process or outcome?

5. What are the national baselines for course-taking behavior, attrition, and retention of various student cohorts (SMET majors, non-SMET majors, prospective K-12 teachers) in various types of academic institutions (i.e., by Carnegie classification)?

6. What aspects of undergraduate, graduate and postdoctoral study from abroad should be considered for adoption or adaptation in the US? What are effective ways of including an international perspective in US SMET higher education?

7. What are the enablers, barriers, and determinants of institutional innovation, sector and organizational systemic change, performance improvement, and organizational learning?

8. How do colleges and universities adapt to shifting environmental demands?

F. Longitudinal Studies of Student Outcomes

1. What is the effectiveness of various factors (pedagogic approaches, curricular approaches, co-curricular approaches including research and teaching experiences, SMET content choices, SMET breadth and depth choices, etc.) on academic achievement, career choice, and career "success" (especially in the preparation of K-12 teachers and their resultant effectiveness).

2. How can transitions between the academic and employment sectors be improved?

II. APPLIED RESEARCH IN HIGHER EDUCATION

A. Transition from K-12 to Undergraduate

1. Affective Preparation for Undergraduate Study

2. Academic Content

3. Pedagogic Styles

4. Alignment of K-12 Graduation Standards and Assessments with Undergraduate Entrance Standards and Assessments

B. What are the international differences in the preparation of K-12 teachers and how do these correlate with K-12 student knowledge and performance?

1. Institutional Structures for Pre-Service Education

2. Pre-Service Program (including recruitment, curriculum content and pedagogy, and field experiences)

3. Induction (including financial, community and school support)

4. Certification/Licensure

5. Perceived Social "Status" of Prospective Teachers by Peers and Instructors

C. Transition from Undergraduate to Graduate

1. Affective Preparation for Graduate Study

2. Academic Content

3. Pedagogic Styles

4. Alignment of Undergraduate Graduation Standards and Assessments with Graduate School Entrance Standards and Assessments

D. Transition from Graduate to Postdoctorate

1. What have been the patterns in usage of postdoctoral appointments over the past 50 years? What are the correlates of changes by field (e.g., employment prospects, growing complexity of the field)? What are the perceived advantages and disadvantages of postdoctoral appointments? What aspects of postdoctoral appointments can be changed to the benefit of the appointees (e.g., employment benefits, clearer definitions of roles and responsibilities, etc.)? Are there special characteristics of holding a postdoctoral appointment abroad that should be considered? What about postdocs held at national laboratories rather than at universities

E. What are the International Differences in the Preparation of Undergraduate and Graduate Faculty and How do these Correlate with Undergraduate and Graduate Student Knowledge and Performance?

1. Institutional Structures for Faculty Preparation and Development

2. Induction

3. Certification/Licensure

APPENDIX B. Partial Listing of Journals Devoted to Educational Research and Practice

Advances in Education Research
Advances in Physiology Education
American Biology Teacher
American Educational Research Journal
Australasian Journal of Engineering Education
Biochemical Education
Bioscene: Journal of College Biology Teaching
CUR (Council on Undergraduate Research) Quarterly
Educational and Psychological Measurement
Educational Research
Educational Research Quarterly
Educational Studies (U.S.)
Educational Technology
Educational Technology Research and Development:
Educational Theory
Electronic Learning
Engineering Science and Education Journal
European Journal of Engineering Education
The International Journal of Engineering Education
Journal for Research in Mathematics Education
Journal of Biological Education
Journal of Chemical Education
Journal of College Science Teaching
Journal of Economic Education
Journal of Educational Measurement
Journal of Educational Psychology
Journal of Educational Research
Journal of Education in Science and Technology
Journal of Engineering Education
Journal of Environmental Education
Journal of Geoscience Education
Journal of Interactive Media in Education
Journal of Natural Resources and Life Sciences Education
Journal of Negro Education
Journal of Professional Issues in Engineering Education and Practice
Journal of Research and Development in Education
Journal of Research in Science Teaching
Journal of Statistics Education
Journal of Technology Education
Journal of Women and Minorities in Science and Engineering,
Mathematics and Computer Education
Review of Educational Research