RESEARCH ON TEACHING AND LEARNING IN ENGINEERING[*]

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Introduction

Educational research has the same standards of scholarship and rules of inference that apply to engineering research. Conclusions should be supported by data and reported in the context of relevant theory and prior studies; their limitations should be determined by statistical analysis and fully reported; and the studies on which they are based should be subjected to peer review and described in enough detail for others to be able to replicate them and either confirm or refute the conclusions. For most of the history of engineering education, however, the standards were not applied to most studies of teaching and learning, and most journal articles and conference proceedings have been variations on the theme "We tried this method and we liked it and so did the students."

While there is certainly value in descriptions of innovative instructional programs and materials (which is basically what those papers consist of), as a rule nothing much happens as a consequence of their appearing in print. It is not hard to understand why. Faculty members have their hands full trying to keep up with existing demands on their time; they are not eagerly looking for new ways to do the things they do. Before they would consider making a significant change in the way they teach, most of them would need answers to several questions:

1. Did students taught the new way learn significantly more than traditionally-taught students? Did they end with significantly greater skills? Which skills? *How do you know?*
2. Are students taught the new way significantly happier, more self-confident, more positive about the subject and about their education than traditionally-taught students? *How do you know?*
3. How much are any observed benefits due to the new method and how much simply to how good the teacher is? If an average teacher used the method, what kind of results might he or she expect?
4. How much does it cost to implement the new approach—for materials and supplies, and more importantly, in faculty and student time and effort? Do the proven benefits justify the costs? *How do you know?*

There are several reasons why until fairly recently, few engineering education studies addressed those questions in a systematic way. One is that most engineering professors are not trained in educational research and seldom interact with specialists in pedagogy and assessment of learning, so they have little idea of how to approach a research study involving human subjects. Another problem is that until recently there has been little incentive for engineering educators to undertake the effort required to learn how to do educational research. They had few

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opportunities to get grants, couldn't use their department's graduate students, and couldn't publish educational research studies in the "right" journals (that is, the journals that count when promotion and tenure decisions are made). Even if they were successful at educational research, they would probably still be treated as second-class citizens by their more traditional colleagues.

All of that is slowly starting to change now, and a growing subset of the engineering professoriate is now engaging in engineering research and development. Most are still working from a base of unfamiliarity, however. While I don't pretend to be an expert on educational research, in the nearly two decades I've been doing it I've developed some ideas about how to do it and, equally importantly, about mistakes to avoid. The purpose of this talk is to share those ideas.

A Brief Informal History of Engineering Education Research

From the first issues of the various transactions and journals published by the American Society for Engineering Education beginning in 1910, reported studies of engineering courses and curricula were almost exclusively descriptive and anecdotal, and their authorship was limited to a miniscule percentage of the engineering professoriate. In the 1980s and early 1990s, three developments occurred that led to significant increases in the quality of engineering education research and in the number of engineering professors involved in it.

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Development 1. The National Science Foundation Enters the Game

Grants for educational research have been available for many years from private corporate and philanthropic foundations such as the Sloan and Kellogg Foundations, but they were rarely tapped by engineering educators before the 1980s. In the late 1980s the National Science Foundation allocated funds to support educational research and development through its Division of Undergraduate Education (DUE), and in 1990 the first DUE research grant was awarded. At about the same time, the NSF began to provide funds for large single-campus research centers devoted to specific themes, and in 1991 it funded the first two of several multicampus engineering education coalitions (EECs) initiated in the next few years. Millions of dollars in grant money now became available through these different entities to support educational research studies, and growing numbers of faculty members responded with proposals.

Another NSF initiative that promoted educational scholarship was to require grant awardees to include educational components in their proposals and research studies. The best known example is the prestigious Faculty Early Career Development Program (CAREER), which has induced many talented young engineering professors to integrate educational research and development into their disciplinary scholarship. Many faculty members who write CAREER proposals are initially inclined to pay little attention to this requirement and simply add a page indicating that they will bring some undergraduates into their laboratory or teach a new graduate course on their research area. They discover, however, that the educational components of the proposals tend to determine whether or not proposals get funded (every proposal that makes the first cut has an excellent disciplinary research component), and most of the awardees end by putting equal efforts into both components.

Development 2. Scholarship Reconsidered

The second major development was the publication in 1990 of *Scholarship Reconsidered* by Ernest Boyer, then head of the Carnegie Foundation for the Advancement of Teaching. Boyer proposed that there are four forms of academic scholarship:

- *Scholarship of Discovery*: frontier research
- *Scholarship of Integration*: applied research that builds on and extends frontier research
- *Scholarship of Application*: applied research that directly benefits society
- *Scholarship of Teaching* (later renamed *Scholarship of Teaching and Learning* or *SOTL*): studying education and using the results to improve it

Boyer argued that all four scholarships were equally important components of the academic mission, but only the scholarship of discovery was fully recognized and rewarded by the prevailing system of faculty performance evaluation. He and his successors at the Carnegie Foundation have called on academic leaders to restore the balance among the four and in particular to recognize educational scholarship as a legitimate faculty pursuit, which if done successfully should be recognized and rewarded no less than frontier research is. The response of university administrators to this call has been slow but steady.

Development 3. The Revised ABET Engineering Criteria

The object of the outcomes-based accreditation system introduced by ABET in 1996 was to improve engineering education, not to promote educational scholarship. Nevertheless, the system has definitely had the latter effect. First, engineering students must now be equipped with a broad array of technical and professional skills, which requires instructors to use a broader range of instructional materials and methods than have ever before been used in engineering education. Moreover, the faculty must now assess the extent to which the students are in fact acquiring those skills, which amounts to determining the effectiveness of the new methods. Once all that has been done, the logical next step is to write up the results and present them at a conference and/or publish them in a journal, at which point the faculty members doing the work have become educational scholars.

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The combined effect of these three developments has been to raise both the quantity and the quality of engineering education scholarship. Membership in the ASEE has steadily grown and the numbers of proposals to present at the Annual Meeting of the ASEE and the annual Frontiers in Education Conference have skyrocketed, as have the number of submissions to the *Journal of Engineering Education* (which recently switched to an all-research format), the *International Journal of Engineering Education*, and journals of professional engineering societies such as AIChE, ASCE, and IEEE. Educational scholarship is not yet a mainstream activity for engineering faculty members and there is still a long way to go before it routinely counts toward promotion and tenure, but the movement toward that goal is unmistakeable.

Categories of Educational Research

Most engineering education research studies fall into one or more of four broad categories.

- *Classroom research*. Course instructors collect data on the performance and attitudes of their students while the course is under way and use the data to address perceived problems and improve instruction. Statistical analyses of the data are generally not carried out, and the results might be published as part of a descriptive report at a conference or a journal that publishes descriptive papers but would probably not qualify for an archival journal such as the *Journal of Engineering Education*. The classic reference for this genre of scholarship is *Classroom Assessment Techniques* by Angelo and Cross.

- *Quantitative research.* Academic performance and student survey data are collected and subjected to statistical analyses to reach conclusions about the effectiveness of the course instruction or the particular aspect of it being studied. There would normally be a second group with whom the experimental group would be compared. In the most rigorous of such studies, the second group would be a control group matched to the experimental group in background and skill levels (among other attributes) that does not receive the experimental treatment. Matched control groups are usually difficult or impossible to set up, though, and so the comparison group might be a class given by the same instructor in a prior year or one given by a different instructor in the same year or students who took the same course in a study reported on in the literature.

- *Qualitative research.* Students are observed in class and/or videotaped while working or studying and/or interviewed and taped individually or in focus groups. Transcribed records of the observations and interviews are coded and analyzed to identify common patterns and draw inferences about underlying causes of observed behaviors. This type of research is fairly common in the social sciences but still relatively rare in engineering education. It is extremely time-intensive and can normally only be done with a small student population. In a *mixed methods* study, quantitative research is done with a large number of students and qualitative research is done with a small subset of them to shed light on the causes of the quantitative study outcomes.

- *Meta-analyses.* Published studies of an instructional method or tool are analyzed collectively. In some cases the analysis is a simple numerical count (e.g., of 36 published studies of ____, 27 reported a statistically significant positive effect on student performance relative to a comparison group, 8 reported no statistically significant effect, and 1 reported a statistically significant negative effect). In other cases, the results of all the studies analyzed are put on a common numerical scale and statistical analysis is used to determine a collective effect.

Studies of the three latter types are all fundable and publishable in archival journals. They may be standalone projects or components of disciplinary research projects, such as CAREER Award projects. Examples of all three can be found by browsing recent issues of the *Journal of Engineering Education.*

Assessing Student Outcomes

Suppose you're carrying out a quantitative study to investigate the effectiveness of an experimental instructional method in a course being taught by you or a colleague. What data can you collect that would enable you to conclude that the method is effective?

I will suggest some possibilities, all but the first of which require a comparison group that takes the same course taught without using the method being evaluated. If the experimental and comparison groups are well matched in initial skill levels and the experimental group significantly outperforms the comparison group, one can infer that the instructional method was effective, with a level of confidence dictated by the same statistical analysis that led to that inference. Here are some things that can be assessed:

- *Grades or pre-test/post-test gains on a standardized test* (such as the Fundamentals of Engineering exam) *or a concept inventory* (such as those being developed at Arizona State University and the Colorado School of Mines for transport phenomena and thermodynamics). The results for the experimental group can be compared with published norms for the assessment instrument.
- *Grades or pre-test/post-test gains on a non-standardized test, such as a final examination in the course.* If you use this metric, make sure the test assesses the skills the experimental method is supposed to help students develop. If a desired outcome is the development of critical thinking skills, for example, and the test requires little or no critical thinking, you should not be surprised if there is no statistically significant difference between the experimental class and the comparison group.
- *Quality of a product, such as a written project report or oral presentation, or a process or product design or a concept map.* To get a reliable assessment of quality, use a checklist or rubric that itemizes and assigns ratings to each evaluation criterion (e.g., technical accuracy, clarity of explanations, creativity,...); have multiple raters fill the form out independently for both the experimental and control groups (ideally without knowing which product comes from which group); and then have them reconcile their ratings.
- *Retention in the curriculum and/or in school.*
- *Students' self-ratings or pre-class/post-class gains in ratings of confidence in specified skills.*
- *Students' attitudes regarding the effectiveness of the instruction at helping them learn acquire the specified knowledge and skills.* Assess with questionnaires, focus group interviews, or structured individual interviews.

Attitude ratings are the most common and the weakest (least convincing) assessment measure. Always collect them—if the students can't stand a method it's important to know it—but try not to make them the only measure you use.

Differences between Engineering Research and Educational Research in Engineering

There are many more similarities than differences between traditional disciplinary research and educational scholarship (setting aside classroom research). Both require well-formulated research hypotheses, careful reviewing of the relevant published literature, clear plans to collect and analyze data, interpretation of the data in the light of relevant theory, and sound analysis to justify and set limits on any conclusions inferred from the experimental outcomes. Both are without value if they are not disseminated in enough detail that others can replicate them, and both should be subjected to rigorous peer review before their conclusions are accepted and built upon.

There are differences, however, of which the most significant is that there is no way to conduct an educational research study as “clean” as the research studies engineers are accustomed to. Students are human beings, and human beings are infinitely variable in ways that tensile test specimens and objects in projectile motion and even fruit flies are not. A student’s performance in a class is determined the instructional methods used (which generally include but are not limited to the variables under investigation), and also by the skills and personality of the instructor and by the student’s prior background, relevant skill levels, interest in the course subject, motivation to be in the class, attitude toward the instructor, self-confidence in general and specifically in the skills required in the course, current workload, extracurricular activities, health, and an uncountable number of factors in his or her personal life. It is consequently impossible to set up an experiment to control for every factor that affects performance except the one you wish to study. The implication of all that variability is that any conclusions drawn from a typical educational research study must be considered far more tentative than engineering professors are used to drawing in their technical research.

There are two ways to raise the level of certainty of inferences from educational research: (1) study a student population numbering in the tens or hundreds of thousands (there are such studies), or (2) rely heavy on replication of results. If an instructional technique is found to have statistically significant positive effects on student learning in many studies conducted with different populations and different instructors, it is reasonable to conclude that the technique works—the more studies and the greater the diversity of student populations, the firmer the conclusion. This means that you don’t have to insist on results that are statistically significant with $p<0.0001$ before you attempt to publish your research, and your results may simply reaffirm conclusions drawn in other studies rather than having to be completely original. If your methods are sound and your results shed light on the subject, you can consider the research successful and publishable.

Another difference between disciplinary research and educational research is that whenever research is done that involves collecting and analyzing data on individual students (or more generally, on human subjects), the participants must sign consent forms and the project must receive prior approval from the university Institutional Review Board, which guards against ethical abuses by researchers (such as giving students a sense that their grade depends on their willingness to participate in the study).

Questions to Ask When Planning an Educational Research Study

Educational research is just as difficult and time-consuming as traditional research, and there is no point in undertaking a project that is not important enough to justify the time and effort it will take. Here are some questions I suggest you ask before taking the plunge. Your answers should help you determine whether to commit to the project, and they will also be critically important in your attempts to persuade funding agencies to support the project and potential collaborators to join it.

1. What is the general topic of the research? What is its importance to science, engineering, education, and society?
2. What is the research problem to be addressed? Why is getting the solution important?
3. What approach will I take (quantitative, qualitative, or mixed)? What experiments will I conduct? What analyses will I perform? What models will I develop? What resources (money, people, time) will be required for the work?
4. Exactly how will the projected results contribute to the solution of the research problem?
5. How might solving the problem impact science, engineering, education, and society?
6. Should I seek funding? From whom?
7. Should I try to find collaborators? What knowledge and skills should they have? How should I identify them?

If you can't make a good case for the importance and potential breadth of impact of your project, you will have very little chance of persuading anyone else that the project is worth carrying out and you might consider dropping it and trying something else.

Choosing Collaborators Wisely

Yet another important difference between engineering research and educational research is that if you are an engineering faculty member, you were trained to do the first one but not the second one. Consequently, when you first set out to do educational research there are probably a lot of things you don't know about how to do it. There are two ways to deal with this problem. One is to attempt to make yourself an expert on working with human subjects, designing and implementing quantitative and/or qualitative experiments, and performing the appropriate statistical and other analyses to draw justifiable inferences from the results. The other is to seek collaborators who already know how to do all those things. Especially when you're relatively new to the field, you're almost certainly better off taking the second of those paths: among other advantages, you will have an easier time persuading funding agencies to support the work if the project staff collectively has strong credentials in every aspect of the research.

So how do you identify suitable collaborators? I suggest using three selection criteria:

1. *Choose people with knowledge, skills, and experience that complement yours.* They might be educational psychologists, cognitive scientists, sociologists, communication specialists, statisticians, or colleagues in engineering or other technical disciplines who have made it up the learning curve in the areas you lack. To assess the suitability of

potential collaborators in this respect, talk to them, check with others who know them, and search out and read some of their publications.

2. *Choose people who can write.* If someone is a poor writer, you will have a terrible time trying to decipher and rewrite their contributions to proposals and papers, and your chances of getting the proposals funded and the papers accepted will be much lower than they would be if your collaborator wrote clearly and persuasively. Again, read some of their publications and see if they make sense to you.

3. *Choose people you would enjoy working with.* If you dislike or don't respect faculty colleagues and even if you just find them mildly irritating, you're probably better off looking elsewhere: their technical skills are unlikely to compensate for the strain of having to reach consensus with them on the hundreds of large and small details that inevitably arise in research. Before you commit too much, spend time with potential collaborators and check with others who know them.

Grantsmanship

As with disciplinary research, you don't want to waste time writing a proposal to an agency which is highly unlikely to fund it. Here are several ways to identify government agencies and private foundations that fund studies of the type you are contemplating:

- Ask colleagues who do similar research.
- Find related papers in the literature and look in the acknowledgments section to see if a funding source is listed.
- Check funding agency Web sites (NSF, NIH, education-related foundations, and the Department of Defense if homeland security is involved). Try the Community of Science Web site (*www.cos.com*).
- Consult your university's Office of Contracts and Grants.

Once you have identified a target agency, don't write a complete proposal until you have reason to believe the project is fundable. Check the agency's requests-for-proposals and the list of recent grants they have awarded. Then:

- Write a pre-proposal outlining the project, including its importance and relevant prior work. The pre-proposal should be short (2–3 pages) and should include the following information:
  - What problem are you going to solve?
  - Why is it important?
  - What will you do? (Plan of work in broad outline form)
  - How will what you do help solve the problem?
  - How will your work add to prior work in the field?
  - How will you know if you have succeeded in meeting your objectives? (Assessment)
  - What impact will this work have outside your university? (Breadth of impact)
  - What will you do to make the impact as broad as possible? (Dissemination)
  - What qualifies you and your co-PI's to do this work? Why is your institution the right place to do it? (Don't be modest!)

- Contact the agency by phone and explore their interest. Sell the project! (Don’t do this before you have written the pre-proposal—you’ll need to be ready with answers to those questions.)
- If the program director is receptive, send the pre-proposal, follow up with another call to answer questions and (hopefully) get the go-ahead to write the full proposal.
- In the full proposal, carry over all the tips for the pre-proposal, plus the following:
  - Summarize the prior work in the field thoroughly, being sure to cite all the key contributors to it (some of whom will probably be reviewing your proposal and looking for their names in your list of references).
  - Emphasize the potential breadth of impact of the work. Agencies don’t want to fund projects with benefits that don’t go beyond the institution where the work is done.
  - Pay careful attention to the assessment and dissemination plans. Inadequacies in either one can be enough to sink a proposal.
  - Follow the agency guidelines and prescribed format for proposals to the letter. If there’s a 15-page limit, don’t submit 15¼ pages.

Dissemination

No matter how good your work may be, if no one knows about it then you might as well not have done it. Include as broad a range of dissemination outlets as you can in the proposal—publications, conference presentations, campus seminars (on your own campus and elsewhere), a Web site, digital libraries of instructional material (SMETE, MERLOT, etc.), and personal contacts.

The most important outlet is usually refereed publications. Here are several tips on publishing:

- Read recent issues of relevant journals to get a feeling for the type and length of articles they publish and writing style they seem to favor;
- Schedule regular writing times—e.g., 30 minutes per day—rather than waiting for long blocks of time to open up;
- Aim for prestigious journals, but not too prestigious for the quality of the research. Journals may take 6–12 months or more to make a decision, and if you have at best a 1% chance of acceptance you’re better off lowering your sights immediately rather than risking delaying publication by a year.
- Make your reference list thorough, for the same reasons you should do so in proposals.
- *Get internal reviews first.* Get colleagues, friends, graduate students, and anyone else you can find to give you the harshest critique they’re willing to give before you submit to a journal. Revise the paper according to the comments you get that strike you as reasonable. Then submit. (You should do this on any proposal or paper you ever write, whether it’s technical or educational.)

What if you do all that and the paper is still rejected? Don’t take it personally—it happens to all of us. If the editor leaves the door open for revision and resubmission, revise the paper taking into account the reviewers’ comments and resubmit with a cover letter detailing how you responded to each comment. Your chances of acceptance should then be very good. If the rejection is final, revise and submit to another journal.

Recommended Reading

1. P.C. Wankat, R.M. Felder, K.A. Smith, and F.S. Oreovicz, "The Scholarship of Teaching and Learning in Engineering," in M.T. Huber and S. Morreale, eds., *Disciplinary Styles in the Scholarship of Teaching and Learning: Exploring Common Ground,* Ch. 11. AAHE/Carnegie Foundation for the Advancement of Teaching, Washington, 2002.

2. *Journal of Engineering Education, 94*(1), January 2005. A special issue of the journal reviewing the state of the art of engineering education research in several critical areas.