Paper # 2003-1133

Teaching Engineering, Teaching Science: A Two-Sided Coin

By

Kazem Kazerounian
Robert Vieth

School of Engineering
University of Connecticut
Storrs, CT 06269-3139

"A scientist builds in order to learn; an engineer learns in order to build."
Fred Brooks

"The scientist seeks to understand what is; the engineer seeks to create what never was."
Von Karmen

Abstract

An ambiguity exists in our definitions of the roles and professional responsibilities of scientists and engineers. This ambiguity extends to (or perhaps stems from) educators' different approaches to teaching "science" and "engineering." A poor understanding and appreciation of this difference profoundly affects the demographics of higher education as well as those of the professional workforce.

At the K-12 levels, educators' attempts to introduce engineering into the curriculum typically focus on either science education or technology training. The ideas in this paper arise from numerous discussions and from the collective work of the NSF Galileo Fellows and their Directors at the School of Engineering, University of Connecticut. Our objective involves defining the concepts of science and engineering and laying down a foundation for exploring the differences, similarities, and interdependencies of these notions. We aim to develop and crystallize the philosophy driving our efforts to offer K-12 students a meaningful exposure to engineering concepts and principles, and to expand the scope of students' eventual career choices to include engineering.

Introduction

The National Academy of Engineering (www.nae.org) lists the greatest engineering achievements of the 20th century:

1- Electrification
2- Automobile
3- Airplane
4- Water Supply and Distribution
5- Electronics
6- Radio and Television
7- Agricultural Mechanization
8- Computers
9- Telephone
10- Air Conditioning and Refrigeration
11- Highways
12- Spacecraft
13- Internet
14- Imaging
15- Household Appliances
16- Health Technologies
17- Petroleum and Petrochemical Technologies
18- Laser and Fiber Optics
19- Nuclear Technologies
20- High-Performance Materials

A close examination of each one of these fields reveals the evolution, over decades and centuries, of our understanding of natural phenomena and our ability to quantify these. However, the history of engineering achievements also reveals a process in which knowledge of the mathematical and natural sciences converged with the skills of critical judgment and creativity, an understanding of economics, the adoption of trial-and-error processes that embrace failure, and the desire to create technological miracles. This amalgamation is now known as "engineering."

On the surface, "science" and "engineering" denote distinct activities, and their definitions leave little room for ambiguity. The American Heritage Dictionary defines these terms as follows:

> **Science:** The observation, identification, description, experimental investigation, and theoretical explanation of phenomena.
>
> **Engineering:** The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems.

However, in education--and in practice--the connotations of these terms differ subtly and the boundaries between the two disciplines become less distinct. The resulting ambiguity profoundly affects our interpretation and identification of these terms in the real world.

At the K-12 levels, educators' attempts to introduce engineering into the curriculum typically gravitate to and focus on either science education or technology training. Are there any pillars of engineering education that can resist this unintended divergence? We believe there are: a paradigm and culture of "decision making."

The ideas in this paper arise from numerous discussions and from the collective work of the NSF Galileo Fellows and their Directors at the School of Engineering, University of Connecticut. Our objective involves defining the concepts of science and engineering and laying down a foundation for exploring the differences, similarities, and interdependencies of these notions. We aim to develop and crystallize the philosophy driving our efforts to offer K-12 students a meaningful exposure to engineering concepts and principles, and to expand the scope of students' eventual career choices to include engineering.

An Overview of the History of Modern Engineering Education

Engineering education in Europe and the United States has gone through at least three distinct phases in the past 50 years. Soon after declaring war on Germany in 1941, the U.S. Congress authorized the Engineering Science Management War Training Program (ESMWT) to administer the training and development of technicians working with industrial and defense machinery and in other defense-related plants. In Great Britain, similar legislative acts and governmental initiatives were established. In the post-war era, large numbers of war veterans with significant informal, hands-on technical training entered formal engineering programs. The particular circumstances of these events shaped the subsequent culture and pedagogical paradigms of engineering education. In the 1950s and early 1960s, in the United States and in Europe, engineering education heavily emphasized learning by doing and hands-on skills. As a result, students emerged from these programs as highly trained engineering technologists who were able to produce practical, workable systems and technical machines. Engineering schools in Asia and the Middle East adopted similar approaches.

In the late 1960s, the 70s and early 80s, the space race, nuclear era, Cold War, energy crisis, and emergence of computers began to transform engineering education. More complex applications exceeded the limits of the engineers' intuition and demanded a superior mastery of the natural and mathematical sciences, in addition to a detailed knowledge of specific technological fields. The paragon of engineering education became one in which students entered a program well-versed in mathematics and sciences and graduated with an even greater mastery of these areas. The pendulum had swung to the opposite side, with theoretical aspects of engineering predominating. Engineers were being like trained just like scientists.

In the late 1980s, experts in industry began to question the pedagogical premises of "knowledge transfer." Their assessment was negative. Engineers, they claimed, generally lacked the skills needed to excel in an increasingly competitive environment. They cited skills relating to critical thinking, team dynamics, societal and cultural awareness, communication, creativity, problem solving, economic analysis, and so on, skills that scientists were rarely expected to have mastered. In response to these criticisms, educators responsible for designing engineering programs, first in the United States, then in Europe and finally in other parts of the world, renewed their attempts to strengthen the "design component" of engineering curricula. Executing this transformation proved more difficult than they had anticipated. The "design components" they introduced were, in most cases, scarcely more than exercises in the rigorous synthesis of various applications of the same fundamental sciences. Many engineering educators felt very uncomfortable abandoning a structured and rigorous scientific paradigm and adopting the more flexible approach required in "design." Nowhere was this more apparent than in ABET's (The Accreditation Board for Engineering and Technology) design requirements for engineering curricula in the 1980s [1], which spelled out an extremely rigid (and quantifiable) method for eliciting "creativity!"

In the 1990s, the evolution of engineering education continued. Over the past decade, ABET advanced a major reform effort designed to encourage curricular innovation and to improve the accreditation process. These efforts have given rise to new criteria for evaluating engineering programs, *Engineering Criteria 2000 (EC2000)* [2], which have once again shifted the emphasis of engineering curricula, this time moving away from using prescribed measures and toward evaluating student outcomes in a process of continuous self-assessment and improvement.

These new accreditation criteria have sparked much debate among engineering educators. The new paradigm that they eventually establish, in combination with other forces of change (such as globalization, employment patterns, and engineering automation), will shape engineering education over the next two decades.

National Engineering Education Initiatives at the K-12 Level

Several groups have launched efforts to encourage high-school students to embark on engineering careers. Most of these focus on enrichment or extracurricular activities, designed to promote interest in and awareness of engineering as a profession. For example, JETS, formerly the Junior Engineering Technical Society, organizes activities, events, competitions, and special programs and materials that introduce high-school students to the world of engineering.

Project Lead the Way of the National Alliance for Pre-Engineering Programs has undertaken the most comprehensive approach to pre-engineering curriculum development. Their program seeks to facilitate partnerships--among higher education, the private sector, and public institutions—that will promote the inclusion of engineering in pre-collegiate curricula. The program currently operates in 25 states in cooperation with states' departments of education and receives funding from corporate sponsors and private foundations. Project Lead the Way's four-year sequence of core pre-engineering courses offers professional development opportunities for educators, and facilitates a mentoring program that draws from the academic and private sectors.

In this brief paper, we cannot present a detailed analysis and assessment of the effectiveness of these programs. We can however, propose that although these programs might help address the problem of low engineering enrollments, they do not successfully prepare students for college engineering programs, which are traditionally among the most rigorous of all degree programs. We feel that current reform efforts lack a thorough and in-depth understanding of the similarities and differences between "engineering" and "science" and the implications of these distinctions for engineering education at the K-16 level and beyond.

Who is an "Engineer"?

Numerous definitions of "engineering" appear in the literature [3-8]. Although these definitions vary in form, they share, more or less, a common perspective. They all view engineering as a profession that applies the fundamental knowledge of natural and mathematical sciences to the development of systems and technologies that meet specific human needs.

Most experts cite at least two major areas of expertise common to both "engineers" and "scientists:"

- A solid, basic knowledge of the natural, physical, and mathematical sciences
- An in-depth knowledge of one's own field of practice

These prerequisites have persisted through decades of change and numerous pedagogical environments. Engineers who have not mastered these do not qualify for the profession. Programs that fail to ensure mastery of these do not achieve their mission.

These common areas of expertise create a strong bridge between engineering and science. Science forms the foundation of engineering. Without a profound understanding of nuclear physics, engineers could never harvest nuclear energy. Conversely, engineering, by providing superior tools, has contributed significantly to scientific research and advancement. Yet even if they are drawing from similar areas of knowledge and applying similar skills, "engineers" and "scientists" often travel paths that rarely intersect.

We propose that it is the role of decision making in engineering, along with educational paradigms and cultures that cultivate decision-making skills, that marks the most significant distinction between these two disciplines.

Decision Making

The process of good decision making is systematic.

1. **Formulation of the Problem:** Determining what precisely is the problem to be solved. If the problem is overwhelmingly complex, break it down until a relatively clear understanding of the several related but smaller problems is achieved. This is not a trivial process. Indeed it is key to good decision making. Engineering and science call for very different approaches to formulating problems.

2- **Systems Modeling:** Determining the factors that will substantially affect outcomes and assessing the interaction of these factors through a systems approach. These factors generally fall into two major categories:

- Variables that parameterize physical quantities. (This is where fundamental scientific knowledge plays a role.)
- Factors that, though not easily quantifiable, are, in most cases, more critical than

those in the first category. Examples of these second type include:

- Culture and ethnicity
- Globalization
- Ethics
- Economics
- Political landscapes
- Etc.

3- **Risk Assessment:** Determining the probabilistic factors that influence outcomes, for example, a lack of knowledge about the factors in (2) above and the associated costs of this gap. Some risks are obvious and well documented in the engineering and standardization literature (designs for specific life expectancy, for example). Others are much more difficult to predict. Engineers should be able to take risks without an unreasonable fear of failure.

4- **Team Work and Communication:** Communicating well and demonstrating the ability and willingness to work in teams. Engineers must be flexible, adaptable, and resilient.

5- **Problem solving:** Bringing creativity to the challenge of problem solving. Engineers must possess a high degree of creativity. Problem solving is not a rigorous walk on a deterministic path.

6- **Judgment:** Evaluating various options and trade-offs and identifying the best possible solution. Whereas in science there are unique answers to deterministic problems (such as a global optima in mathematical models), in engineering there is no globally best "design." For example, there are at least ten different designs for wine bottle openers, each with its own function (and beauty).

Decision Making, A Process Far More Complex than Problem Solving

Much of what engineers do is solve problems and make decisions. In fact the engineering profession is constantly making a series of decisions. The process of *decision making* is far more complex than the process of *problem solving*. Problem solving focuses primarily on creativity and the traits attributed to creative people. In contrast, decision making calls for prudent exercise of a series of choices, with controlled risk, against the cost and the consequences of the probable and potential outcomes.

The introduction of creative problem solving to engineering curricula represents a major, and praiseworthy advance. Nevertheless, this addition to engineering curricula falls short of providing a comprehensive and systematic approach to developing the skills of engineering decision making.

Engineering educators at all levels must continue their efforts to cultivate creativity in students by creating learning environments that encourage risk taking and analogical reasoning, that tolerate ambiguity, and reward diverse interests, personalities, and modes of thinking. They must support the playfulness, humor, idealism, and ambition that spark students' creative abilities. They must provide ample opportunities for brainstorming, in all areas of the curriculum. They might even want to introduce methodological exercises designed to tap into creativity (methodology and creativity, though often perceived as antithetical, are not incompatible). Formal methodologies such as "Inventive Problem Solving" or " Pough's Method"offer valuable templates from which to build these exercises. However, while the ability to bring creativity to problem solving is highly desirable, some excellent engineers possess mediocre creative skills. In the end, good engineering decisions are practical, workable, economic, and may be even elegant, but they are not necessarily creative.

Methodologies for making good engineering decisions using "process design," "concurrent engineering," and "process control" have found their way into modern engineering profession and have profoundly changed industrial practices. Correspondingly educators must move beyond traditional approaches to problem solving and develop the specific skills of decision making.

Decision Making in the Classroom

Promoting a classroom culture that nurtures decision making skills represents the first step in successful engineering education. And while a flexible learning environment is desirable at all levels, it is particularly critical for K-12 students, who should focus more on method than on specific scientific and technological subject matter.

Unfortunately, educators often tend to focus narrowly on isolated elements of "decision making"—for example, the systems analysis, or variables that parameterize physical quantities, or even creative problem solving, discussed in the previous section--rather than the process in its entirety.

Fear of ambiguity and fear of failure create the most significant barriers to broad adoption of an educational paradigm that seeks to develop skills in decision making. To overcome these psychological obstacles, we must help both educators and students make the transition from traditional scientific or mathematical analysis to engineering modeling and synthesis, which do not define the notions of "correct" and "incorrect" in terms of outcomes (unless, of course, these violate a physical law).

Developing a rich collection of case studies that compel both students and teachers (at the K-12 levels) to work outside their comfort zone of well-defined problems and definitive analysis represents one methodology that might ease this transition. These case studies should feature challenges whose complexity resides in the broader nature of the problem, not in the physical model. In addition , complicating factors such as culture, ethnicity, globalization, ethics, and economics should play a prominent role. Case studies, or educational units, will not only invoke students' understanding of the underpinning sciences (which is prerequisite), but also on skills relating to creative problem solving, critical thinking, team dynamics, communication, and social awareness. In short, all the ingredients of a good engineer.

Conclusion

Many factors beyond the traditional fields of engineering, mathematics, and the natural sciences are assuming a prominent role in the continuous evolution and reform of engineering education in the United States and the world. In this paper, we argue that such factors unequivocally distinguish engineers from scientists and that a clear understanding of the differences between engineering and science must drive reform efforts in engineering education. We propose that effective "decision making," and not merely problem solving, characterizes good engineering. Engineering educators in general, and educators working at the K-12 levels in particular, need to be cognizant of this characteristic and must devote significant effort to developing it through novel approaches in their engineering curricula.

Acknowledgements

The ideas in this paper arise from numerous discussions and from the collective work of the NSF Galileo Fellows and their Directors at the School of Engineering, University of Connecticut.

Graduate Fellows include Jennifer Shea, Walter Doll, Elias Faraclas, David Giblin, Reza Nassiri, Tony Cyril, Angel Rodriguez, Sonia Sanches, Bill Ballard and Kim Rodriguez.

References

1- Winfred M. Phillips, George D. Peterson, and Kathryn B. Aberle, **Quality Assurance for Engineering Education in a Changing World**, The International Journal of Engineering Education, vol. 16, no. 2, 2000, p.97-103.

2- **Engineering Criteria 2000, Accreditation Board for Engineering and Technology**, available at http://www.abet.org

3- R. Natarjan, **The Role of Accreditation in Promoting Quality Assurance of Technical Education**, Int. J. Engng.16, 2, 85-96, 2000.

4- D. Q. Nguyen, **The Essential Skills and Attributes of an Engineer: A Comparative Study of Academics, Industry personnel and Engineering Students**, Global Journal of Engineering Education, Vol. 2, No. 1, 65-76, 1998.

5- D. Thom, **Engineering Education and the New Industrial Revolution**, Int. J. Engng. Ed.,14, 294, 1998.

6- S. Florman, **The Civilized Engineer**, St. Martin's Press, New York, 1987, pp. 76-77.

7- E. Ferguson, **The Imperative of Engineering, in Connections: Technology and Change**, ed. J. Burke et al., Bonds & Fraser, San Francisco, 1979, pp. 29-31.

Biographical Information

Kazem KazerounaiN is a Professor of Mechanical Engineering at the University of Connecticut. His research interests include mechanical design, robotics, chaos theory, and engineering education. He is the chairman of the ASME Robotics and Mechanisms Committee, and the general conference chairman for the ASME Design Engineering Technical conferences and Computers in Engineering Conference 2002. He has served as the as Associate Editor of the ASME Journal of Mechanical design, and International Journal of Mechanisms and Machine Theory.

Robert F. Vieth is the Project Director for the Galileo Project, and a staff member of the School of Engineering. He recently resigned as a research scientist after 25 years at UCONN and is pursuing a Ph.D. in science education at that institution. He is a Fellow of the Connecticut Academy for Education in Math, Science and Technology.