An Approach to Undergraduate Engineering Education for the 21st Century

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Abstract – **The complexity inherent in the newest technologies as well as the complexity inherent in the multiplicity and diversity of societal needs and perspectives in relation to those technologies calls for a new approach to undergraduate engineering education. We believe this new approach requires a paradigmatic shift from a linear reductionist mindset to a nonlinear holistic mindset. To accomplish such a shift in undergraduate engineering education we propose a new context, new content and new pedagogy to reinforce the context and content. The latter includes the concept of *praxis*, a set of personal, group and professional practices, which have the goals of internalizing knowledge, enhancing self-awareness and embodying the values of a new integrated culture of engineering. We believe that the program advocated in this paper can be implemented within the constraints of the normal 4 year curriculum by utilizing the ABET humanities and ethics requirements more effectively.**

Index Terms – Undergraduate engineering education, context, content, pedagogy, paradigm shift.

INTRODUCTION

This paper advocates an approach to undergraduate engineering education based on a new paradigm in which engineering is practiced with social as well as technical expertise. To produce engineers who are competent to participate in the development of 21st Century technology, we believe that the role of an engineer must be redefined from being a developer of technology for society to being a participant in the societal process through which technology shapes society. Such a redefinition will not only call for a different kind of education, but will also attract a greater variety of students. Currently based almost entirely on science, the engineering curriculum tends to attract primarily those students with science as their focus. The redefinition we are proposing is based on an integration of science and the humanities and, as such, would attract students with a wider range of interests.

We intend for our approach to go far beyond merely adding a number of elective courses in the humanities, social sciences and perhaps one or two courses on ethics. Simply sending engineering students for short visits to the other side of the campus doesn't really bridge the gap between the "two cultures" which C.P. Snow already commented on in 1956. Rather, our proposed approach is based on three premises: (1) technology shapes society as much as it is shaped by it, (2) the newest technologies (e.g., bio-, nano-, and information technology), because they can so dramatically impact the ecology of life and hence evoke debate from a number of societal stakeholders, require the engineer to have developed social and emotional as well as technical intelligence, and (3) a new integrated culture needs to be generated for the engineering profession rather than simply mixing elements from the two existing cultures. To support this integration, we also propose introducing the notion of "praxis", by which we mean a set of personal, group and professional practices that embody this proposed new culture. By engaging with these practices experientially, students ultimately would be supported in developing a new relationship to themselves, their profession and their world. Our intention is to educate engineers to be able to integrate two kinds of complexity: the complexity inherent in the newest technologies and the complexity inherent in the multiplicity and diversity of societal needs and perspectives in relation to those technologies.

This paper describes three elements required for such an approach: (1) a new context for undergraduate engineering education, (2) a set of five core competencies and a special interdisciplinary approach to the Capstone Design experience, both of which introduce new content into the curriculum and (3) a new pedagogical approach for reinforcing the context and supporting the delivery of the new content. The ideas advanced in this paper stem from both an upper division engineering ethics course that two of us (WEK and GH-K) have been teaching during the past 5 years [1] as well as an NSF sponsored workshop that the three of us organized in April 2003 entitled, *Ethics and the Impact of Technology on Society* [2]. Some of the ideas presented in this paper are new and some have already been incorporated into existing programs at colleges and universities, both nationally and internationally.

PRIOR CALLS FOR REFORM

Recently, a number of prominent engineers have been calling for both a broadening and a strengthening of the engineering curriculum. Joe Bordogna [3], Deputy Director at NSF and former Assistant Director of Engineering, writing in "The Bridge", a publication of the National Academy of

Engineering, proposed a new approach to engineering education. Referring to this new approach, he speaks of a "holistic undergraduate curriculum" that is congruent with the complexity, uncertainty and ambiguity inherent in the technologies currently being developed. In his view, engineering ethics and societal values should be included as part of the design process itself. Furthermore, he says that students will need to shift their focus from problem solving to problem formulation and from avoiding chaos by seeking order to learning to live with ambiguity. In fact, with respect to the complex nature of technology and its relationship to society, Bill Wulf [4], president of the National Academy of Engineering, also writing in "The Bridge", stated that the most challenging issue facing the engineering profession in the 21st Century, is how engineers will communicate to both the general public and to the relevant social institutions about the costs (i.e. risks) of complex technology as well as its benefits.

In addition to many articles, there have also been a number of recent initiatives aimed at undergraduate engineering curriculum reform. Most notable among these was the National Science Foundation's "Engineering Education Coalitions" Program. A recent evaluation of this program [5] stated that, "The Coalitions Programs has had many important impacts during the first five years, but these cannot be said to be the comprehensive and systemic new models for engineering reform [which had been] anticipated." Furthermore, in a project called “Deep”—Deconstructing Engineering Education Programs [6]—an extensive review of recent activities aimed at increasing diversity in the undergraduate student body of engineering schools was conducted and several significant conclusions were drawn:

> "Essentially no attempts have been made to revise the engineering curriculum itself so as to promote diversity, even though it is clear that the curriculum is central to what defines an engineering education. Instead, most diversity initiatives aimed at the undergraduate engineering student population have started with a curriculum which is known to be unattractive to women and minorities, and have tried using 'add-ons' or minor changes to rectify the situation. We believe that this approach fails because the curriculum is fundamentally flawed and because the rigors of the typical engineering program are not conducive to permitting 'add-ons' without increasing the pressure on students."

In another important evaluation of recent reform initiatives, Juan Lucena [7] examined engineering undergraduate education in light of Globalization and the ensuing need for producing a "flexible" engineer." According to Lucena, flexibility can be defined as the ability to solve different kinds of problems under different kinds of constraints and circumstances, so that the needs of the community, the nation, and humanity are served.

HISTORICAL BACKGROUND

Prior to War II, engineers developed technology for building America's infrastructure (bridges, sky-scrapers, hydro-electric dams, etc.) in support of industrialization and a rapidly growing population. Emerging from the war, the engineering profession moved into new areas of activity that included space exploration, nuclear energy, jet aircraft, modern telecommunications, computers and semi-conductor devices. To support this, a new paradigm emerged for engineering education: the science based engineering curriculum. For the last 50 years or so, most engineering programs in the United States have been based on this model.

This science-based curriculum has served us well. We have landed people on the moon; we have developed robotic assembly lines; we can communicate instantly at any time of day or night with anyone anywhere in the world via the Internet or with cell phones; and we have produced hand-held PDA's that have more memory and speed than the computers which were originally used to design our arsenal of nuclear weapons! Moreover, in the United States technology has contributed significantly to national security, to economic growth, and to an assured food supply. We have created a technology-based military that is second to none along with an enviable record of economic performance and prosperity driven by technological advancement.

Our society is now entering a new period of scientific achievement that brings with it not only new frontiers for technology, but also a new set of challenges for the engineering education community. Recent scientific breakthroughs include the mapping of the Human Genome [8], the development of Complexity Theory [9], the discovery of Supramolecular Chemistry and Self-Assembly [10], a new understanding of Ecology and Self-Similarity [11], the application of Plasma Physics to manufacturing processes [12], and new advances in Network Theory [13] and Nanoscale Science [14]. This has led to whole new fields of engineering such as Biotechnology, Nanotechnology, and various aspects of Information and Nuclear Technology. These breakthroughs have profound implications for our society, not the least of which is the need for the next shift in the paradigm of engineering education similar to the shift that occurred after World War II [15].

CHARACTERISTICS OF THE NEWEST TECHNOLOGIES

Because our proposal rests on the premise that the newest advances in science and technology require a concomitant new paradigm for engineering education, it is useful to describe some of the basic differences between the science and technology of the 20th and 21st Centuries. The key distinction we draw here is between engineered systems that are **complicated** and those that are **complex**.

The context within which Industrial Age technologies (20th Century) are understood and upon which our current undergraduate engineering education is based, is a Newtonian/Cartesian worldview. This worldview is atomistic (reductionist), deterministic (based on cause and effect) and dualistic (a subject/object split). In other words, the properties of these complicated systems: (1) are understandable by studying the behavior of their component parts, (2) exist independent of the observer, and (3) are deduced from "objective" empirical observations. Such complicated Industrial Age technologies include aerospace vehicles, chemical and nuclear plants, and computer and robotic systems.

Three fundamental aspects of our post-industrial age (21st Century) technology are complexity, uncertainty and ambiguity, and complex systems have one or more of the following characteristics: (1) holistic/emergent—the system has properties that are exhibited only by the whole and hence cannot be described in terms of its parts, (2) chaotic—small changes in input often lead to large changes in output and/or there may be many possible outputs for a given input, and (3) subjective—some aspects of the system may not be describable by any objective means. Also, in addition to the aleatory and epistemic uncertainty inherent in 20th Century technology [16], 21st Century technology is characterized by indeterminacy [17] (bifurcations far from equilibrium). Furthermore, because of our limited experience with such systems, there is a high level of ambiguity (i.e. "variability of legitimate interpretation based on identical observation or data assessments.") [18].

IMPLICATIONS FOR ENGINEERING EDUCATION

Inherent in these latest scientific advances is a shift from a reductionistic to a holistic paradigm. In a reductionistic paradigm, the engineer is considered to be separate from and independent of the technical system that he or she is developing. In other words, technology is assumed to be value neutral and the engineer's personal point of view to be irrelevant. In a holistic paradigm, the engineer is understood to be part of the technical system in that his or her point of view and values are necessarily expressed in the technology. The limits of subject/object dualism are exposed in the holistic paradigm and hence, in order to act responsibly, the engineer must understand the implications of this recursive relationship. As noted by Deborah Johnson, far from being neutral, the artifacts produced by engineers already have embedded in them, "knowledge systems, social institutions, social practices and human relationships. If we redefine technology in this way, we open up the possibility that there can be a broad range of ethical issues 'in' technology [19]." In other words, there is an inherent connection between the artifacts produced by engineers and the context from which engineering is practiced.

Thus, the engineer of the 21st Century needs to develop competence not only in technical matters, but also in humanistic concerns. By humanistic we mean understanding oneself and how one relates to nature and to the social environment. This doesn't mean that an engineering student would merely take a few extra courses in the humanities or even that he or she would need to take a double major. Rather, it means that educating the next generation of engineers must, at its core, bridge the gap inherent in the reductionist paradigm. In fact, it is precisely because this fragmentation is so apparent in the challenges posed by the newest technologies that we can even recognize the need for the integration.

DESIGN OF THE PROGRAM

Our proposed program has three essential elements: (1) a new context for undergraduate engineering education which is based on a shift from a linear to a nonlinear paradigm, (2) new and revised content consistent with this context and (3) new and existing pedagogical approaches for both reinforcing the context and supporting the delivery of the content.

I. Context:

Based on our research into past curriculum reform initiatives, we believe that one of the unique aspects of our approach is the introduction of the principle of "context". To use a simple analogy to explain what we mean by context and how we intend to use it, consider a magnet placed under a piece of paper with some iron filings sprinkled randomly on the paper. In a short amount of time the iron filings will take on the shape of the magnet's field. If one were then to shake up the iron filings so that they are again randomly distributed, it would only take a short amount of time before the filings again line up with the pattern of the field. Context is like the magnetic field that gives shape and meaning to the content. It is for this reason, we believe, that so many reform interventions ultimately fail or produce only marginal results. That is, merely shaking up the curriculum (content and pedagogy) without reorienting the field (context) may produce some temporary changes, but it will only be a matter of time before the curriculum returns to its previous condition.

Context, as we are using the term, refers to the mindset or paradigm within which we propose to frame an undergraduate engineering education. The contextual shift we are speaking of is from **linearity** to **nonlinearity**. As long as the world is perceived merely as a machine and the engineer as a mechanic, then one can successfully interact with the world in a linear way. However, when we begin to recognize that the world is alive and that we are part of it, linearity is no longer appropriate. We can no longer look at the parts of a system as being separate from the whole, cause and effect relationships no longer always apply and instead of reductionistic systems, we are dealing with complex adaptive systems organized in recursive, non-linear feedback loops of which the engineer is a part.

As we develop a new kind of science, so too must we develop a new kind of engineer. By making explicit the paradigm that underlies this new science, we gain insight into the context necessary for a new curriculum to educate the new kind of engineer. Thus, the engineer of the 21st Century must think non-linearly and see him or herself and the world as an inter-connected whole. From this new context the content and pedagogy follow and become the means for developing the shift in thinking characteristic of the new mindset.

II. Content

What is organizing our thinking about the content for this new program is the question: "What will it take to develop in engineering students those core competencies that are necessary to function successfully in a 21st Century engineering environment?" In addition, we see setting competency goals as being consistent with the ABET 2004-2005 Criteria for Accrediting Engineering Programs [20]. Here are the five key competencies that we have thus far identified and which were our guiding principles in developing the content:

- **Maintaining a high level of technical expertise**. This always has been characteristic of the engineering programs in the USA. We do recognize, of course, that many of the core science and engineering science courses that make up the current undergraduate engineering curriculum are taught from a linear context. However, students would be provided with a framework for participating in these courses, so that they understand not only the usefulness but also the limits of linearity and can see it as a foundation for comprehending more complex systems.
- **Developing an historical perspective in order to understand the nature and role of contexts and paradigms**. In order for engineers to understand the societal context within which engineering is practiced and technology is developed, as well as to appreciate the nature of paradigms and paradigm shifts, we propose an educational component based on an understanding of: (1) the role of the engineer in society through time and across cultures, (2) the role of ethics as it pertains to technology through time and across cultures; including a history and overview of ethical ideas (from both a Western and an Eastern perspective) of the Axiological Age (800-200 BC), Modernity (1600-1900) and Post-Modernity (1900-Present), (3) the influence of science, mathematics and technology on the thinking of these historical periods, and (4) the evolving role of Engineering Standards and Practices as well as Professional Codes of Conduct.
- **Developing an understanding of systems and networks in order to see the world holistically/ecologically**. The traditional approach to teaching engineering systems and network theory relies on an understanding of linearity and reductionism. Using concepts such as General System Theory and Cybernetics [21], new advances in Network Theory [22,23] and computer codes for solving nonlinear systems, we intend for the student to understand: (1) the underlying physical and mathematical concepts of nonlinear systems and networks, (2) open living systems (e.g. ecological systems) and the principles of emergence [24] and sustainability [25], and (3) social systems as networks [26].
- **Developing "ethical know-how"**. The following are characteristics of what we are calling "ethical know-how" [27,28]: (1) flexibility and a tolerance for ambiguity, (2) an appreciation and concern for dealing with diverse points of view in multi-stakeholder situations, (3) the ability to engage in dialogue, (4) an eco-centric and world-centric perspective, (5) an ability to be self-reflective and transparent to oneself and others, and (6) a shift from a mindset characterized by control to one characterized by participation.
- **Developing leadership and entrepreneurship**—If engineers are to participate in the development of technology as a societal shaping process, then a new level of leadership is required. Among other things, leadership is the ability to participate in complex, multi-stakeholder conversations, such that the right questions emerge and people are motivated to take action. Although this is a very extensive topic, this element could be addressed in the Capstone Design experience, which focuses on In-Service learning.

III. Pedagogy

Central to our pedagogical approach is the notion of "praxis"—personal, group and professional practices that internalize knowledge and lead to more effective action. These practices would be focused on reinforcing the new context and supporting the delivery of the new content. In addition, they would expand the capacity of students to access knowledge beyond the traditional analytical approach.

We distinguish between three types of knowledge. The first type is "explicit knowledge"—an analytical knowing based on conclusions derived from empirical observation. Most educational systems offer this type of knowledge and, indeed, it would continue to play a large role in our approach as well. The second type is "tacit" or "embodied knowledge"—a knowing that is acquired through personal experience leading to more intuitive and spontaneous action. In-service or action learning are examples of ways for gaining this type of knowledge, in which the background practices of the profession are internalized. The third type is "primary knowledge"—a knowing derived from an awareness of "interconnected wholes rather than isolated contingent parts" and, as Professor Rosch of the Department of Psychology at Berkeley points out, action derived from such an awareness can be "shockingly effective" [29]. By appreciating the nature of context and how one makes meaning, this type of knowledge can lead to innovative thinking and creativity. In fact, techniques and practices to access primary knowing have been part of the creative arts and various spiritual traditions for centuries.

Following is a list of these kinds of practices that can reinforce the nonlinear context:

1. Personal Praxis (leading to personal mastery)—Praxis is based on learning by doing and involves practices that help embody knowledge so that it becomes second nature. (As an example, consider what is involved in knowing when to shift gears while driving a car without having to look at the tachometer.) Praxis can also increase self-awareness, which we consider to be the foundation of ethical behavior. Examples of personal practices include:

- **Body awareness**—An enhanced ability to sense one's own body and to listen to its signals provides a greater basis for the student to be more in attunement with him or herself, which in turn allows for a clearer access to all three types of knowledge. Examples might be yoga or one of the martial arts.

- **Contemplative practice**—Various forms of meditation have been used for centuries to ground awareness and to increase self-reflection. For example, meditative practice can cultivate concentration that "makes it possible to see connections that may not have been visible before" [30]. In fact, it's interesting to note that two NBA championship teams (the Chicago Bulls and L.A. Lakers) had a meditation practice as part of their training programs. In addition, Amherst University recently sponsored a symposium, which explored bringing contemplative practices into higher education [31,32]. In our view ethical behavior requires, at a minimum, the capacity for self-reflection.
- **Creative self-expression**—Whether it is music, dance, painting or sculpting, an experience of regularly developing and expressing one's creativity allows the student to access the third type of knowledge—primary knowledge.
- **Nature as Teacher**—For centuries Nature has been viewed as a portal for human beings to touch deeper regions of themselves. We believe that a personally experienced and alive relationship with Nature is the basis for an authentic commitment to sustainability.

2. Group Praxis (leading to inter-personal competence)— Examples of group practices include:

- **Dialogue—**Our model of Dialogue stems from the work of the physicist David Bohm [33], who identified a process by which assumptions and judgments are exposed, perceptual filters are revealed, real listening can occur and true communication is possible. William Isaacs, Founder of the Dialogue Project at the MIT Sloan School of Business, defines dialogue as literally the art of thinking together. He observes that rather than just an exchange of words, it is an embrace of different points of view [34]. We believe this is an essential capacity for engineers to work effectively with others in the new complexity of their profession.
- **Presencing—**Presencing [35] is a process developed by Peter Senge, Otto Scharmer and others at the MIT Sloan School of Business that provides access, both individually and collectively, to one's deepest capacity to sense and shape the future. Based on a synthesis of direct experience, leading edge thinking and ancient wisdom, it taps into deeper levels of learning for discovering new possibilities.
- **Inquiry based learning and team learning**—As part of the program (particularly the Capstone Design experience), assignments would be formulated in such a way that students are encouraged to work on them through independent research, both individually and in teams. Moreover, team learning is useful in training students in participatory skills, which include dialogue among divergent points of view.

3. Professional Practice (gaining engineering experience)-- Examples of professional practices include:

- **In-Service or Action Learning (Design projects with engineering companies, communities or government agencies)**—This would provide students with practical real-world experience early on in their education. In some cases, students might participate with Engineers for a Sustainable World (formerly known as "Engineers Without Frontiers") on projects for Developing Countries. Such a practice would allow students to address complex design issues regarding technology and society beyond those usually considered at the senior level. Examples of this are the Engineering Projects in Community Service (EPICS) program at Purdue University [36] and the Professional Praxis program at Smith College [37]. Many engineering schools, both nationally and internationally, have Co-operative (CO-OP) programs that can satisfy this program element [38,39,40,41,42].
- **Mentoring and Shadowing**—Students would have the opportunity to shadow practicing engineers during the time that they are working on their projects. MentorNet could be used to partner students with mentors from industry [43].

CONCLUDING COMMENTS

A natural question that might arise in conjunction with the program advocated in this paper is whether or not it can be accomplished within the normal 4-year undergraduate engineering curriculum. We have experimented with some of the personal and group practices in our engineering ethics class, and several of our colleagues have been experimenting with some of the professional practices in the capstone design experience. Based on this experience, we believe that with judicious and innovative application of the humanities and social science requirements (usually between 5-7 courses for most accredited programs), of technical electives and of the new ethics requirement (ABET 2000), existing courses can be revised and new courses developed to achieve the goals of this program within 4 years. For example, personal praxis could be included in a one unit practicum associated with an engineering ethics course, while group and professional praxis could be included as part of the capstone design experience. A course on network theory, as described above could be treated as a technical elective.

We believe that the next step should be a pilot program for 35 to 50 students (incoming freshman) from different engineering disciplines, who would come together during their four years to participate in this program. Although we feel a sense of urgency, we believe it is necessary to take one step at a time, and we believe a pilot program is a necessary one.

In conclusion, as Domenico Grasso, states [44]:

> "Engineering faculty members cannot…simply consign young students to the other side of campus for humanities classes and consider our obligation for providing a broad and liberal education fulfilled. It is for us to complement the rigors of our technical classes with the humanistic

framework within which engineering resides…as the new century unfolds, the engineering profession is uniquely poised to redefine a liberal education. Thoughtfully considered, engineering education can develop in our students a fundamental and visceral view of the unity of knowledge and the ability to use this knowledge for socially responsible and reasoned judgment. The academy must lead the way in engineering a liberal education of our students and prepare them for the leadership roles required of a technologically advanced society."

We cannot agree more!

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