2006-1722: HOLD PARAMOUNT: DESIGNING AN ENGINEERING EDUCATION TO OPEN MINDS AND SERVE THE PUBLIC GOOD

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to Open Minds and Serve the Public Good

Engineering and Public Policy Division

ABSTRACT

The NSPE Code of Ethics states engineers "*shall hold paramount the safety, health and welfare of the public and conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession...*" In this paper, rather than discuss the teaching of engineering ethics, the author will explore the significance of the "*hold paramount*" principle for engineering educators, the engineering curriculum, and its potential impact on public policy and the student body. *How* we teach engineering may in fact dominate the ethical and societal lessons we wish to teach. Questions explored include: How can one effectively and practically teach fundamental engineering concepts in a way that will equip our graduates to embody these ideals? Does this principle instruct us, as engineers and educators, to focus on public policy and our society's technological choices? Finally, how can we, as engineering educators teach students to responsibly tackle the ethical questions that lack a quantitative answer? An introduction of a three-tiered approach to encompass the range of issues involved is described. Specifically, strategies from chess instruction, computer games, and the potential power of a graduate with knowledge of competence, self, and the surrounding world are described.

In Gunn and Vesilind's book of the same name, *Hold Paramount*,[1] they skillfully prod and poke at the ethical issues facing professional engineers that most of us wish would just go away. If everyone were honest and honorably motivated then these problems wouldn't exist, we rationalize. We find these tricky questions of right and wrong, honesty and duty to self and society, frustrating, puzzling, even painful. As they aptly state: "There seem to be lots of different points of view in ethics, and not everyone will agree on the best solution to an ethical problem. Too bad the ethicists can't be as efficient as the engineers." Ethical problems are different from engineering problems, right? In engineering problems there is one right answer. But in the profession of engineering the real quandary lies not in the answer, but in asking the right questions. After a brief calculation an engineer decides, yes, a beam can support 500 kg.

But will that amount be enough to ensure *safety*? As the knowledgeable and professional decision maker, engineers are responsible for ensuring that the correct questions, those that *hold paramount* the values expressed in the Code of Engineering Ethics, get asked and then honestly and with all due effort accurately answered. The realm of asking questions, as opposed to solving problems, falls under the domain of scientific inquiry, not science *per se*. The careful process of formulating hypotheses based on observations, collecting information, and, by a rigorous and transparent process, validation or invalidation of the initial hypothesis teaches how much there is that we really do not know.

A recent article by Wyatt[2] describes how small-scale original experimentation can motivate and inspire students to create and critique their own processes of scientific inquiry. Looking at the current educational approaches without engaged inquiry, Wyatt's article, "Extending Inquiry-Based Learning to Include Original Experimentation," gets to the heart of the current educational problem when she describes how much of teaching relies on formulaic *demonstrations* where the student is expected to observe, analyze, and apply the (supposedly) derived understanding to either similar or more advanced problems. Yet the process of demonstration can only be truly effective if the receiving audience is already well versed in the parameters and interrogated relationships. New vocabulary, ideas, and interactions require deep mental engagement, repetition, and re-shaping of initial impressions to be fully assimilated into one's repertoire. Watching a couple tango across the dance floor, or even a professor derive an equation on the chalk board, does not mean that one can get up and repeat it, much less understand and express the subtle and important layers of interlaid meaning.

The overdependence on poorly resolved demonstrations leads students into habits of dishonest learning.[2] Some of it is outright cheating, but much of it is the lack of self-interrogation. If they understand enough of the math or the units of an engineering problem, then they can get an answer, and, if it is right, then they just move on to the next puzzle. Rarely do they stop and say, "I can do this problem, but I really don't understand it." As students get accustomed to understanding only enough to parrot responses then they are likely to be afraid to ask questions like "Do I really understand this material?", "Can I explain this concept clearly?", and "What does this mean?" Questions like these can bring the whole house of unanswered questions down upon them. We have not equipped them to confront their own unknowing. And it doesn't take much imagination to see that this lack of comfort with self-inquiry leads to avoidance of much harder ethical questions like "What unexpected effects might this technology have?", "Is this technology safe, sustainable, or in society's best interest?" Tractable questions are doable and hence more comfortable, like "How much does it weigh?" or "How much will it cost?"

In the nightmare of the Chernobyl incident, managers in Moscow mandated from afar tests of the nuclear power plant, and the engineers proceeded with the tests despite a progression of six different alarms that foretold of the meltdown.[1] This could never happen here and now, right? And yet what questions should have been asked to prevent the space shuttle Challenger explosion, or more recently the breaking of the levies in New Orleans? These technological "meltdowns" also had warning alarms that were ignored, questions not asked, and answers that few adequately questioned. Engineers must ask the right questions about technology, but also about human nature and even about Mother Nature. But to do this they must be broadly educated in order that they may "think for themselves and to make reasonable decisions"[1] that affect individual lives, the environment, and society.

Confronting the difficult questions must coexist with a "willingness to be wrong." That is, some of these ethical questions will not have exact, easily agreed upon answers. And as a consequence an answer, even a carefully thought out and well-reasoned one, may be wrong. When an engineer knowingly ventures into the realm of the unknown they must be willing to confront their own fallibility. It can be a humbling experience. Students of Wyatt's examples have been provided with a roadmap of questions, investigations, discussion and critique, then finally iteration. As they experience the unknown in a structured supportive environment they begin to take the leap toward becoming independent thinkers. As she remarks, they are getting better grades and retaining material longer. She has broken through their fear and rather instilled in them an open-mindedness to seek out the best, rather than just the right, answers to their own questions.

An unwillingness to be wrong,[2] ignorance of people and the world, and untapped inner creativity, leave us with students who are closer to "intelligent robots,"[1] rather than "flexible and fluid, both willing to rethink and redesign."[2] When an engineer hits an impasse in a real life problem they must have an arsenal of tools: knowledge, creativity and a moral compass that requires them to say, "I don't presently have a good enough answer." This willingness to confront the unknown, to say "I don't know" without shame, opens the door for him or her to seek help and explore further. Knowledge of the environment and the world helps one to ask those questions that are meaningful to society and sustainability, to prevent cultural and environmental insensitivities or disasters. And an awareness of one's own inner creativity helps us to pull back from a tough problem, refresh, and find a new perspective or resources, rather than plowing onward to a definite, but poorly designed conclusion.

A New Engineering Education

Asking tough questions, a willingness to be wrong, the need for a broad education, and "the safety, health, and welfare of the public…" – what exactly does this have to do with *how* we teach engineering?" you might ask. Everything.

> *How can we effectively and practically teach fundamental engineering concepts in a way that will equip our graduates to make concrete these ideals embodied in the "hold paramount" principles?*

The engineering education we typically provide gives few examples of a "willingness to wrestle with difficult questions." With over-packed, inefficient engineering curriculums, it dramatically curtails students' exposure to the insights of social and technological history, the environment, professional ethics, global affairs, even the creative arts. In the engineering classroom where they spend the majority of their time, the examples that students see are perfectly laid out. Incorrect answers are rarely explored, only graded wrong. We professors provide doable prescribed problems, not wanting to confuse the class or appear less than knowledgeable. Yet they, as weakly formed thinkers, need to see and correct mistakes for themselves. And we as educators need to see and understand the weak links in their reasoning so that we can focus our help to reinforce their budding understanding of the essential fundamentals and convince them of the inadequacies of their stubborn misconceptions and poor procedural habits.

While Wyatt's prescription of small student-executed original research projects for the broad range of important engineering fundamentals would definitely help open student's minds, comprehensive implementation without a massive overhaul of the current system is unlikely. But the idea of a supervised exploration of the unknown in her paper is suggestive. And an engineering education adaptation of Jeremy Silman's approach to teaching chess[3] I believe will provide a more efficient and workable system, without requiring complete restructuring of our current academic knowledge. Returning to the idea of a willingness to be wrong, Silman's text, "The Amateur's Mind: Turning Chess Misconceptions in Chess Mastery" provides a storehouse of examples of incorrect chess thinking. As with Wyatt's original research projects, the focus is on the underlying thought processes and by showing again and again that mistakes provide ripe opportunities for learning.

Key in this approach is the necessity that we simultaneously increase both the efficacy and efficiency of teaching undergraduate engineering fundamentals, by motivating a willingness to confront difficult question and then allow more room for those much needed electives. To bring this together, I recommend combining three elements. The first two elements come from "best practices" from two arguably opposite sources: Jeremy Silman's strategy of problem selection, analysis, and repetition for chess mastery combined with the efficiency, repetition and incremental learning structure of computer games. The third element is a critical refocusing of student-professor interactions specifically on (1) the technical misconceptions, as appropriately identified by the first two, (2) a greater emphasis on service learning opportunities, and (3) additional time for development and integration of relevant and engaging technical and non-technical electives.

SILMAN'S CHESS STRATEGIES

In Jeremy Silman's text, "The Amateur's Mind: Turning Chess Misconceptions into Chess Mastery," the author illustrates key chess misconceptions and, by explicit examples with detailed analysis provided in an accessible manner, he unlocks, for the amateur, wrong thinking and opens the door to the underlying strategies and more correct understanding. Silman began by getting his students to "talk out loud" their thoughts as they played through game after game. By recording and comparing the transcripts, he was able to detect misconceptions that he had never known they possessed. With a master's perspective, he then organized numerous key examples of missteps into important subcategories. In his book, he feeds the missteps and their critiques back to the reader, in a way inoculating them against the mistakes of their predecessors. Key concepts for each section are highlighted throughout as brief "Tips."

Though aspects of this approach overlap with mastery learning,[4] the emphasis on explicit learning from errors is a different and critical aspect. This approach can be applied on a class by class basis with positive results. However, in my view the real benefit to the student and to society at large, will be seen with the increase in efficiency with a more systematic and department- or college-wide approach. For broad implementation, each specialty in undergraduate engineering education – mechanical, chemical, electrical, civil engineers, etc. – would identify three to six basic and essential concepts, and an associated example problem, for each of the approximately 10-12 fundamental courses. Then a total of 40-60 problems would illustrate the fundamental understandings required for mastery of engineering at a basic undergraduate level. Then some of us would do as Silman did and interview a diverse cohort of our students as they work through each problem. A dynamic catalog of these extracted misconceptions could allow the design of intelligent tests that pinpoint individuals' weaknesses and allow the professors to tailor the lectures, discussion, examples, and homeworks to eradicate the misconceptions. The goal would be true mastery of these fundamentals, not a "60%" which is then curved to equate to a meaningless "B."

Perhaps this sounds too easy. The cynical professor might argue that once the students know what the problems are they will "memorize" those particular answers and never approach understanding, much less mastery. This is where the second element comes into play.

COMPUTER GAME STRATEGY

Computer games are successful for many reasons: instant feedback, iterative and progressive development of difficulty, the ability to try again when the player gets "killed." Yet these same characteristics might prove vital in a teaching tool that efficiently and effectively creates numerous opportunities for a student to work through their own individual weaknesses and misunderstandings. With careful selection and identification of appropriate fundamental problems as described above, computers could be used to design numerous iterations on the same fundamental problem. If a student really could memorize the whole class of problems around that fundamental initiator, than who are we to argue that they have not achieved mastery? And with highlighted "tips" that provided timely wisdom as students work through the material, general concepts will be reinforced when they are most valuable – just after the student made the mistake.

The opportunity for a student to iterate on a particularly tricky part (for that student) will be possible with a computer creating related problems. And the professor could be notified to work with the student to extract their particular "flavor" of misunderstanding so that it can be clarified or made concrete by a hands-on experience. The level of learning could be sloped to suit each individual student, with flash backs to earlier concepts whenever a refresher is needed. Each course and specialty could customize the selected problems to relate to current public problems in specific sub-specialties; the math might be the same, but the concepts taught would feel more relevant and, therefore, more memorable. Such specialization would be worthwhile because it would be retained and useful for years to come. With careful tracking problematic questions would become apparent and could be clarified, eliminated, or subset problems could be identified and integrated to support students' learning of those concepts that are more challenging. Imagine students who could ***all*** solve the fundamental problems of a field. They would know their own mastery and as a consequence would possess the tools and feel empowered to take on more challenging real life problems – that they would be exposed to in their technical (and non-technical) electives!

In front of the chalk board or over the computer, by using studying mistakes to interpret underlying misunderstandings we will, in effect, make over students' attempts at solving even unoriginal problems into a version of Wyatt's "original research projects." No longer would the professor hand out the understanding. Now by focusing on analysis of mistakes the professor is an ally and can model the process of trying to understand a new concept, in this case the as-of-yet-unknown thought process of the student. While simultaneously students watch, listen and learn from each other and the professor's inquiry, in vocabulary they understand, becoming engaged in the process of inquiry into what is wrong with a particular approach and how it can be best improved upon.

The third element re-focusing student teacher interactions and a reduction in the number of specified required courses is in effect the reward of successful implementation of the first two. Students will see themselves developing mastery, like rising to higher levels or scores as on a computer game. Students will be more likely to find support rather than judgment from their professors. And individual interests and a greater awareness of our responsibility to and the needs of society will become relevant topics that motivate service learning opportunities and improved integration of technology and the challenges that surround us.

CONCLUSIONS

This combination of informed teaching based on specified problems and examination of student level mistakes, integrated with repetition and identification of misconceptions in computer game format to achieve mastery has many elements from established and successful teaching methodologies. Together, I am hopeful that they will integrate to make mastery the norm and allow students to see that difficult questions and misconceptions are opportunities for collaboration and development of truer understanding. This approach toward the fundamentals should awaken our independent thinkers early in their undergraduate tenure. No longer passive recipients of a professor's perspective, students so educated will be more efficient learners. Their understanding of the power of honest inquiry will let them see early on why we educators stuck with it so long. As allies, the sky's no limit.

The "*hold paramount*" principles point to the fact that we as educators need a *systemic* solution for our current systemic problem. Though ABET Criteria 2000[5] may have crushed some of the entrenched problems of the past, we need, our students need, and our code of ethics compels us to develop an efficiently and comprehensively integrated system of our combined wisdom. Perhaps this approach will help us move beyond the current situation of too many courses, too little mastery and an approach that necessitates open-book tests and grade-on-a-curve evaluations. We cannot leave real-life experiences to a few seriously demanding upper level engineering projects executed by fewer still admirably committed faculty, inspiring mostly those students who share those particular interests. By reducing the number of prescribed requirements and increasing service learning opportunities, many students will have the chance to put their work where their heart is. There is a lot of work needed by our society in the areas of infrastructure, energy generation, health and environmental safety, to name just a few. Engineering graduates who possess the technical knowledge, a willingness to tackle tough questions, and improved awareness of themselves and the world around them are our best hope for the future.

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