Rethinking Engineering Education

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Abstract— **The necessity of restructuring engineering education has been recognized for many years, but for a number of reasons reform is becoming increasingly urgent. It is not just that current engineering education methods are increasingly obsolete; student cognitive patterns are changing in unpredictable ways, and the complexity of the environment within which engineering is practiced is also increasing dramatically. Half measures that might have been seen as adequate a decade ago are no longer sufficient. What is required is a thorough rethinking of the engineering education framework, centered around a division of engineering students into technical, single expertise, and design capable cohorts.**

***Index Terms*—digital natives, educational innovation, engineering education, sustainable engineering**

I. Introduction

The necessity of restructuring engineering education has been recognized for many years, primarily driven by the significant technological changes of the twentieth century, and the need to attempt to jam ever more material into a four year undergraduate professional degree [1], [2]. While this is a long standing motivation, others have more recently become more important. Among these are the accelerating rates of evolution of the so-called emerging technologies: nanotechnology, biotechnology, robotics, information and communication technology, and applied cognitive science [3], [4]. These emerging technologies do not just complicate engineering on the technology side; they also contribute to a more fundamental increase in complexity that affects all aspects of human activity, including institutional, social, cultural, and economic systems as well as coupled technologies – especially because the effect is not just on systems external to the human, but internal, as the human itself becomes a design space [5]. Additionally, the scale of human activity has continued to expand as it increasingly becomes clear that the integrated human/built/natural systems that characterize the anthropogenic Earth are dramatically increasing the complexity and difficulty of designing, operating, and managing sustainable systems and technologies [4], [6]. Perhaps the most obvious current example is the interest in geoengineering, or massive technological intervention in climate and carbon systems (see Allenby, "Geoengineering: A Critique," in these *Proceedings*).

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All of these developments inevitably have affected the classroom in many ways, perhaps most fundamentally by the change in students. For example, many of today's students are "digital natives" who have been heavily networked since they were toddlers; they are usually intimately familiar with synthetic realities, social networking sites, augmented realities, and mashups that their elders, including most of their professors, may not even be aware of [7], [8]. More specifically, when the students open their laptops in class, it is not just an easier way to take notes; they immediately have access, for the first time in history, to virtually the entire factually heritage of human history through Google™ and similar search engines. Memory is no longer an individual trait; it is universalized, and facts qua facts are no longer worth learning. This does not mean that facts aren't important, because the student needs to be able to use them to assemble patterns and knowledge responsive to particular questions, but it does mean that much of the current educational approach needs to be rethought: the limitation on human cognition shifts from an inability to access sufficient factual material to make a decision, to an inability to make sense of an overabundance of information.

Additionally, the rapidly growing complexity of the world expresses itself in a need for students that, while technically competent, are also able to understand the environmental and social context within which today's engineering occurs [9], [10]. Among other things, this has lead to an increasing focus on industrial ecology, and demands to develop "sustainable engineering" theory, practice, and educational modules [4], [11], [12]. Nonetheless, most education in general, and engineering education in particular, has not made any significant shifts in response, despite a great deal of experimentation over the past few decades [13].

II. The "I" and the "T"

To the uninitiated, it sometimes may seem as if engineering education has been hijacked by Sesame Street; the literature is full of "I's," "T's," and more exotic versions such as "H's" [14]. These are actually quite useful symbols once deciphered: an "I" is a deep specialist in only one area; a "T" is a deep specialist, but with working knowledge and expertise in, and the ability to communicate across, many different disciplines and areas; an "H" is a deep specialist in two areas; and, of course, a "π" is an individual with deep expertise in two areas, and the ability to work in, and communicate across, many different domains. A Ph.D. environmental scientist with a law degree and broad expertise in working on transdisciplinary problems from many different perspectives would be a π, for example, whereas a person with professional degrees in environmental engineering and civil engineering would be an H. An environmental engineer who has been trained to work with non-engineers, and integrate easily into marketing, and product design and production teams, and communicate difficult issues to a public audience, would be a T. The consensus is that I shaped professionals take less time and are easier to train than any of the more exotic variants. More subtly, if the experience of the author is any indication, efforts to train T-shaped individuals will be seen by more conservative faculty as at best a waste of time, and at worst a "dumbing down" of "real" engineering.

There are some serious implications to this seemingly simple dichotomy. First, both T and H professionals are likely to be far more innovative and collaborative in the real world; I-shaped professionals can often work well with each other in the same domain, but find it very difficult to reach beyond their expertise. Given the demands of an increasingly complex industrial and economic environment reflecting serious globalization, the T and H shapes are far more productive than the I. As executives from IBM note ([14] at 261), "occupational descriptions show a clear trend for expert thinking (problem solving) and complex communication (collaboration skills). These findings are consistent with the growth of a knowledge-intensive service economy." Note the dilemma this poses: much of the engineering education establishment believes that producing I-type engineers is the essence of engineering education, whereas the complexity of industry, the globalized economy, and engineering issues in the twenty-first century demand T and H types.

This has another serious implication for engineering students today. Especially in high labor cost regions such as North America and the European Union, it is important for graduating engineering students to be able to justify the premium companies must pay to hire them, as opposed to engineers and technicians from up-and-coming, generally Asian, countries. While outsourcing has been common for at least ten or fifteen years, it has generally been limited to lower skill technical functions. More recently, however, it is clear that the level of competition is not limited to simply rote technical functions. Chinese engineers recently set the world speed record for supercomputing with a design that differed in significant ways from those the U.S. uses, and built a 15-story hotel in six days (in itself somewhat theatrical, but indicative of excellent project management and infrastructure design skill) [15], [16]. IBM now employs more people in India than in the United States; Cisco has recently decreed that 20% of that firm's leadership are to be in India – all of which led *The Economist* to observe that [17], "[f]or American workers the most worrying thing about all this is the flight of brain-intensive jobs to India."

Put simply, I-type professionals are easier to produce using traditional methods, and do jobs that are far easier to outsource to the least expensive region, be it China (for manufacturing and civil engineering, for example), or India (for computer or electrical engineering, or increasingly for chemical and pharmaceutical engineering), or Brazil (biofuel and agricultural genetic engineering), or those countries that are snapping at the heels of the leaders, leading to strong pressure up the value chain across all economies and forms of engineering. Professors produce I-type engineering graduates today in American schools, but they do so based on dangerously obsolete ideas about how viable such an education is in a highly competitive world. By contrast, H and T type engineers are more likely to be able to integrate their engineering into higher level skill sets, including for example the ability to work with local stakeholders and understand local cultures and regulations. They thus offer more value to employers, and are less easy to replace with non-local engineers, especially when many (but not all) schools in the BRIC and upcoming countries tend to produce I-type engineers. The difficulty is that to produce H and T type engineers requires not just adjustments to curriculum, but adjustments to faculty: relatively few existing faculty members are good at, for example, teaching good business writing or discussing the broader social and environmental issues involved in many engineering activities.

This discussion might seem to suggest that a shift from educating I-type engineers to educating T's or H's would be adequate, at least in the short term, to meet the requirements of evolving social and professional environments. Unfortunately, difficult as even that shift is, it is nowhere near adequate given the rapid and accelerating changing conditions facing the engineering profession.

III. THE CASE FOR FUNDAMENTAL CHANGE

The increasing complexity of the world, and changing cognitive patterns that characterize many students, have already been mentioned as challenges to existing engineering education practices. But a brief consideration of the implications of these changes makes two further points. First, what is required is not merely incremental improvements of existing curriculum and educational materials, but deep and fundamental reform of engineering education. Second, the changes involved are so complex that it is virtually impossible to be sure what adjustments in education will be required *a priori*. Rather, what is required is a co-evolution of educational practice and external environment, a conscious effort of continual adjustment.

Consider the change in student cognition [18]. Many engineering educators still teach factual material for its own sake, rather than treating facts as necessary building blocks for cognition in a rapidly changing, already complex, and factually over-determined environment. In the age of Google, this already blinks reality. But it gets worse, because it is not just factual memory or computational capability that is increasingly being transitioned to technology systems, but deeper elements of cognition itself. In particular, "augmented cognition," or "augcog," technologies, in which not just sensory capability, but the integration of disparate signals, their prioritization based on environmental and systems context, identification of response space, choice of appropriate response, and independent action to implement that response, are rapidly being developed in both military and civilian spheres [19], [20]. Such technology, for example, can be seen in military development of autonomous robots, and in commercial development of augcog vehicles, the latter designed so that they can be used by elderly drivers who may have lost some of their cognitive function, or by younger drivers who would prefer to devote their conscious activities in vehicles to texting rather than driving. The cognitive functions that are being transitioned from wetware (brain and body) to software and hardware in these integrated human/technological networks is not peripheral to what we take to be consciousness, but core: perception, understanding, reasoned response to changing environmental conditions.

Such developments raise several critical questions for engineering. First, as a general rule it is unhelpful to require students to learn things that machines can do more accurately and quicker; accordingly, professors need to make themselves aware of those areas where a function is close to being automated, and let their students know. It doesn't mean that students should be unfamiliar with the function; it does, however, mean that a shift in emphasis in how that material is presented is appropriate. When the calculator appeared, it didn't obsolete division, but it did make the need to know how to do long division by hand obsolete. Google does not obsolete facts, but it does mean that they need to be taught for different reasons, and that memorization, rather than understanding, becomes less important.

Additionally, the rapid rate of technological change has not affected all students equally; not every students, especially at large state universities, is a digital native. In fact, the gap between those who are completely at home in social networks and ICT technology, and those who are inexperienced with most ICT products and services, gets wider, not narrower, as the pace of technological evolution accelerates. This puts even more stress on an educational system predicated on manufacturing mental models: teach everyone in relatively large classes the same thing, as if they were the same experientially and cognitively as the professor was when he or she was taught, and make allowances for individual differences only as well as you can in a batch processing system [18].

But there is another issue that is even more challenging: in a world of augcog and increasingly dense networking, what is human cognition? Is the locus of cognition still the Cartesian individual student, or is it the networks of technology and humans that increasingly coalesce around complex questions and designs? What is it that human minds contribute to cognition in networks that is unique, and what is it that can and will be transitioned to technology? And based on what the uniquely human aspect of these cognitive networks is, what do we teach our engineering students? Obviously, it is impossible to answer this definitively at this time, because the technologies are still quite young, and how such networks develop is very poorly understood. But, considering technology trends, and the already profound effects of social networking and information surplus, it is also clearly increasingly dysfunctional to continue to teach as if it were the 1950's.

This in turn leads to a very basic point: in a world of intense national and cultural competition, characterized by unpredictable and fundamental change in virtually all relevant domain – natural, human, and built – and in which technology systems play ever more critical roles, getting engineering education right is not just a duty to students, and to the society that requires competent engineers. It is a matter of national security and cultural integrity. All nations will have access to the cognition that is migrated to machines, or to technology networks, and any gap between what currently is accepted as best engineering education in virtually all leading societies, from Brazil and India and China to Russia, Europe and the United States, is essentially ephemeral at best. But educational systems are highly conservative, and what that means is that the society that gets engineering education right – that learns how to optimize the human component of these increasingly complex networks of engineering cognition – has a chance to obtain lasting cultural comparative advantage. The stakes are not just individual or institutional, in other words; they are existential - at the individual level, the institutional level, and the cultural level.

IV. Restructuring Engineering education

It is probably too early in the general discussion around engineering education to suggest comprehensive and effective restructuring proposals. However, five minimal suggestions are obvious.

First, the model by which large numbers of individuals of widely varying skills and ambitions are taken in to generic engineering education programs is no longer adequate. Rather, engineering should be divided into three tracks: a technologist track, an I-type engineering track, and a T/H-type engineering track.

Technologists are those who are able to use the technical tools of engineering – software design systems, automated ordering systems, cookbook engineering tools – adequately for routine tasks. They will not need the deeper mathematics or disciplinary knowledge that engineering entails today. I-type engineers will essentially follow the path that all engineers follow today: skills identifiable by engineering discipline (computer, electrical, chemical, civil, environmental, mechanical, aerospace, and so forth), with little additional education in non-specialized areas. Design challenges that lie strictly within one discipline would be handled by such engineers. The T/H-types will undergo a longer and much more varied educational program: they will need to learn how to communicate; how to work with others in industry, and in important stakeholder groups; how to explain and discuss technologies (rather than artifacts) with the public; and how to be leaders that are both socially and technologically competent. Such engineers will design and manage technology systems, address design questions that cross multiple disciplinary boundaries, and work effectively on technology issues at a political and social level.

None of these categories are "better" than the other, but they call forth different skills, different educational tracks, and to some extent different personalities. What this split does recognize is that engineering education as currently constituted is increasingly incoherent and dysfunctional, lumping together very different kinds of students with very different goals in a sticky mass that is difficult to justify even today (hence the pressure on engineering education to develop liberal art components, a desirable trend exemplified by programs such as those at Olin, Dartmouth, and Smith [1], [2], [4]). And they will all be necessary in a future increasingly reliant on technology systems, and buffeted by technological change.

Second, engineering education must "zero budget" its content from the basics to the advanced. How much is being taught now that is irrelevant, or better obtained at far less effort on existing ICT systems? Exactly what does the engineering student need to know about materials, about statics and dynamics, about chemistry and math, about biology? Clearly, a working professional needs a good feel for technical aspects of his or her job; but just as clearly recent advances in technology have made at least some content, and certainly many pedagogical approaches, obsolete. Professors are loath do recognize this, but it is the students who suffer from that lack of vision. A deep rethinking of course content across the board is long overdue. Moreover, the rate of change is relentless, which means that a single revision is inadequate; rather, a process for constant revision must be developed and deployed.

Third, engineering education must take advantage of the ICT environment that already exists. Personalized education is a logical and achievable goal, especially for technical aspects of engineering education. For example, one might create a mine site in a virtual world, with challenges ranging from the technical (how to design the regional, local, and facility infrastructure for a major mining project; how to design bugs to process ore), to the social (stakeholder management when environmental and human rights advocates attack the project), to the economic and management domains (e.g., lifecycle costing of engineering decisions; managing a workforce from an unfamiliar culture). If the software were designed in such a way as to be able to track progress of the student, it could help free at least some engineering education from the tyranny of the batch processing model currently almost universally followed.

The advantage of personalized educational processes, of course, is that they allow students to proceed at their own pace, and to spend the most time on those areas where they need additional training, while quickly advancing in those areas where they already have significant expertise. The gap between digital natives and others becomes far less meaningful, because the educational technology itself can compensate to the degree necessary. Moreover, personalized education lends itself to breaking up the model of "undergraduate/graduate/professional practice" career trajectories: all professionals are, at the same time, always students, and modules that reflect rapid technological evolution can be plugged in as appropriate.

Fourth, the engineering education profession must set up an explicit dialog with the educational establishment, and with professionals, to keep up with unpredictable changes. Institutions to do this could be centered at the National Academy of Engineering, at various professional societies – such as the IEEE, ASCE, AIChE, and so forth – and even at individual academic institutions. But such organizations should be small, and very agile, and would need to be protected against the bulk of the academic engineering education establishment, which will almost certainly be hostile. Among its characteristics should be strong connections with leading edge firms in sectors important to engineering as a whole, both because firms are able to provide quick feedback on inadequacies in current educational methods, and because firms are where much of the technological evolution that is shaping the current era is occurring. It should also be connected to the institutional structures of engineering education: the deans' conferences, ABET, and other organizations.

Finally, a skunkworks to test various new methods of engineering education, from the relatively incremental to the radical and foundational, should be established. It is doubtful that even the most creative academic institution will be able to achieve radical, as opposed to incremental, progress on its own, and even if it did, accreditation and other procedures might well lag significantly. Moreover, which avenues are most productive and appropriate is not always clear when one is in a period of rapid change. Under such circumstances, being able to practice, to watch for unanticipated benefits and costs, to socialize new ideas without having them be such a threat to existing practices and teachers, is invaluable.

These ideas will not resolve the fundamental problems currently facing engineering education. But they can help to create an environment, and infrastructure, where engineering education can respond productively and responsibly to the world that, after all, engineers have had such a significant role in creating.

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