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Galloway's 21st Century Engineer: An Essay Review

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Engineering is a profession focused on the practicalities of creating and building things, much as medicine focuses on the practicalities of caring for the body and education focuses on the promotion of learning and thinking. Professions change with the growth of knowledge and experience in the field. *The 21st Century Engineer* lays out an analysis of changes and challenges in the engineering profession that lie ahead in the twenty-first century, along with proposals for altering the shape of engineering education to address current problems, shortcomings, and opportunities. Globalization is a recurring theme in Galloway, but the book focuses on the United States, and proposes that our institutions of higher education should ensure that future graduates keep us at the front of the world-wide pack. This book is one of several that have appeared in the last few years addressing similar themes. *Educating the Engineer of 2020* (National Academy of Engineering, 2005), *Educating Engineers* (Sheppard, et al., 2008), and *Engineering for a Changing World* (Duderstadt, 2009) all illustrate the level and pace of concern about the future in this area. One statistic sets the stage for this discussion: the production of undergraduate and doctoral engineers in the United States has remained steady for the past two decades, during which time degrees from India, China, and Japan have increased by 50 percent.

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Like Galloway, all of these books refer to Friedman's (2006) "flat world" scenario. The idea is that technology (primarily the internet, but also television and jet travel) has made it as easy to connect Mumbai with Los Angeles as it is to connect Los Angeles with Long Beach – maybe easier, given LA traffic. Consequently, our graduates must not only have superior technical competence, but they must also know how to deal with broader contexts such as economics and cost-benefit issues, the environment and sustainability, policy considerations, and so on. In addition, they need strong communication and leadership skills.

Galloway's argument is reflected in the chapter titles: *Globalization, Communication, Ethics and Professionalism, Diversity, Leadership, The Engineer's Role in Public Policy, Engineering Education Reform*, and *Proposal for A Master of Professional Engineering Management*. The other volumes vary in focus and organization, but several similarities stand out. Most of the books call for two major changes in the undergraduate curriculum: (1) more attention to the liberal arts and humanities, and (2) more engagement from the outset in real-world projects with practicing engineers. All of the books express concern about the monochromatic character of engineering undergraduates, i.e., the underrepresentation of minorities as well as women. Finally, all of the books take note of the virtual impossibility of condensing their recommendations into the standard four-year course of study, hence the recommendation that the undergraduate years forego attempts at specialization, leaving that to post-graduate masters programs. The consequence of such changes is fairly obvious. Most companies want graduates who can hit the ground running in a well-defined arena – they aren't looking for generalists, and if they can't find the specialists they need among U. S. graduates, then they will find them in India and China. In principle, the liberal-arts strategy seems worth consideration, but undergraduates would then be responsible for the opportunity costs of extended education, and reorganization of the undergraduate curriculum would call for substantial institutional changes, upsetting both faculty and administration. The volumes provide examples of success stories, but also mention that these rely on leadership, tend to involve younger faculty, and are difficult to sustain.

What is the Problem, and What to do About It?

Deciding what is and is not the "problem" requires some thought. Other than the relative stagnancy in the number of engineering degrees awarded during recent decades, several matters have been at the top of the agenda for engineering educators for more than a century – "engineering educator" is not an oxymoron! Seely's (2005) history is brief but informative. The Society for the Promotion of Engineering Education, formed in 1893, issued proceedings that became the *Bulletin of the Society for the Promotion of Engineering Education* in 1910, then the *Journal of Engineering Education* from 1925 to 1969, thence to *Engineering Education* (1969-1991). In 1991 this journal was divided into *PRISM* for Society publications and the *Journal of Engineering Education* as a scholarly professional journal. The latter devoted entire issues in 2005 and 2008 to the review and definition of the field of engineering education.

Seely (2005) claims that "…the dominant issue [throughout this history] has involved the content of engineering curriculum, including the relationship between theory and practice, the length of the curriculum, and the nature and structure of general education courses, [along with] issues that reflect influences from society at large [which] touch on the general goals and social expectations for engineering and... engineers" (p. 115). None of the volumes delves directly into instructional practices, despite a brief remark that most drop-outs place poor teaching at the top of the list of reasons for changing majors. For example, *Educating the Engineer of 2020* (NAE, 2005) mentions a 1998 study in which 98 percent of respondents reported that poor teaching was the reason for their change in major; no citation was provided, but Seymour and Hewitt (2000) provide a more detailed account.

The recommendations in all these works center on the academic experience – the need for more time (including postgraduate work and internships), a broader curriculum (engineering as the liberal arts degree of the future), a closer connection with practice throughout the undergraduate years, and the assumption that specialization can be handled after the bachelor's degree. In some existing programs, the connection with practice is already incorporated, in part, through a substantial capstone design experience.

Galloway stresses leadership as the most critical goal for reform; the field needs to ensure that, in addition to existing substantive requirements, graduates possess a mixture of project management skills, business acumen, and policy influence, all shaped by an awareness of the global context. Her proposed *Masters of Professional Engineering Management* is designed for individuals with work experience, who seek advanced certification while employed full-time, for whom concentrated courses and distance learning make most sense. In addition to a thesis, the curriculum includes *Legal Aspects*, *Risk Management*, *Project Management*, *Cost Engineering*, *Project Planning and Scheduling*, *Quality Management*, *Communicating Technical Information*, *Responsibility to Society and Professional Issues*, *Teamwork and Leadership*, *Policy Analysis and Decision-making*, *Managing International Projects*, and *Intercultural Communication and Diversity*. Galloway clearly has a specific portfolio in mind, built around a demanding but largely online, off-campus program of study appealing primarily to a subset of civil engineers.

Educating the Engineer of 2020 takes a broader perspective. The fourteen recommendations can be summarized under five headings: (1) the engineering baccalaureate should serve as a pre-professional degree offering the foundation for later post-graduate specialization; (2) project-based activities should support learning from the start of the undergraduate program, and provide a bridge to continuous learning through involvement with professional organizations; (3) reform activities should emerge from local academic administrators and faculty; (4) both national and local groups should pay more attention to preparation during the K-12 years, and (5) an external agency, such as the National Science Foundation, should collect data on significant indicators, especially the impact of reform efforts on retention.

Educating Engineers by Sheppard and her colleagues at the Carnegie Foundation for the Advancement of Teaching deals largely with parameters of the existing undergraduate program, focusing on student overload and isolation. They mention the possibilities of new pedagogies, including technologies that foster concept learning. More than the other volumes, they emphasize the need for balance between technical learning (not necessarily the same as specialization) and skills in teamwork and communication. In the curriculum area, they describe a "spiral" with a "spine," in which first-year students begin with a cornerstone project that engages fundamental technical areas. Students circle through these same areas during the remainder of the undergraduate experience, "weaving design and laboratory experiences through all of the undergraduate years" (p. 201). Sheppard draws on current learning theories, noting the utility of exercises presented without solutions (akin to Vygotsky's [1978] zone of proximal development), and emphasizing the value of approximation and estimation in approaching problems. The volume incorporates examples from field visits to exemplary programs (other volumes mention similar activities, albeit in less depth), but also notes that "we saw few examples of strong connections between engineering learning and the kinds of liberal arts education that could speak directly to issues of the broader context and meaning of engineering" (p. 205).

Duderstadt's *Engineering for a Changing World* from Michigan's Millennium Project portrays reform in broad strokes, coalescing the numerous STEM (science, technology, engineering, and mathematics) reports from the past decade. The summary and accompanying graphics are quite informative. His basic argument is that the world is changing, that engineers should play a central role in these changes, that the United States should be competitive in these activities, and that the U. S. system of higher education provides the most substantial foundation for achieving this goal. His argument rests not on competitiveness for its own sake, but on the notion that our nation has a depth of resources and potential greater than other countries. The paper presents a mix of policies that include attention to the learning environment, and also to fundamental institutional and organizational changes that are likely to place strains on faculty and administrators in higher education. Duderstadt, like others, calls for a supportive role in this effort by the federal government, especially the National Science Foundation, but the responsibilities of business and industry are largely limited to that of client and consumer.

The Faces and Phases of Reform

Recruitment is a common issue in the volumes reviewed here. Given that the K-12 foundations for this profession are quite limited, recruitment is understandably a challenge. Furthermore, in her chapter on *Diversity*, Galloway comments that young women (and probably many young men) are more attracted to the helping professions, and engineering is not on this list. What a contrast with Herbert Hoover's reflections about his career as an engineer: "It is a great profession. There is the fascination of watching a figment of the imagination emerge through the aid of science to a plan on paper..., then move to realization in stone or metal or energy. Then it brings jobs and homes to men..., elevates standards of living and adds to the comforts of life. This is the engineer's high privilege" (Hoover, 1961, pp. 131ff). Unfortunately, this image is not prevalent in today's high schools. Ultimately, despite intensive recruitment programs, enrollment in engineering has actually decreased slightly over the past 20 years, while overall college enrollment has grown by more than 50 percent (Lichtenstein, et al., 2009).

Retention appears as another theme, but Lichtenstein, et al. (2009) suggest that this "is *not* the issue" (p. 16). In a large-scale survey, they found that the proportion of engineering freshmen who persisted to graduation (about 75 percent in their sample) was only slightly less than in other areas such as social and natural sciences, arts and humanities, and so on. To be sure, other studies have reported lower rates. For example, Seymour & Hewitt (2000) and Ohland, et al. (2008) report persistence rates from the freshman to senior years ranging from 37 to 66 percent. Nevertheless, Seymour and Hewitt report that the retention rate in engineering is greater than that in science and mathematics.

In-migration to engineering is another matter. Lichtenstein, et al., (2009) found that, for most majors, more than 20 percent of final graduates enter the major from another field, while for engineering fewer than 10 percent do so, leading to a net loss of 16 percent compared with other majors. Engineering is impermeable for several obvious reasons. First, because the course of study is filled with requirements and projects, changing majors means spending more time as an undergraduate. Second, many general education courses, such as foreign languages, experiences abroad, etc., cannot be applied toward an engineering degree. Finally, students from other programs may be concerned that change to an engineering major will limit their growth as individuals. Surveys find that engineering students report smaller gains in personal and social development, issues that may be of particular importance to women and under-represented minorities (Lichtenstein, et al., 2009, but cf. National Research Council, 2009, which reports substantial improvements in prospects for women who are scientists and engineers at major research universities).

The reports suggest that respect and recognition are also serious issues for the profession. Engineering has the reputation on many campuses of being difficult and rather nerdish. For example, Seymour and Hewitt (2000) report that competitiveness, grading on the curve, faculty inclinations to "overwhelm and weed them out," and the experience of "drinking from a fire hose" (p. 415) during the early undergraduate years are all troublesome matters for engineering students. All the reports convey the stenotype that engineers work with things, not with people, an image which carries a grain of truth. Today's negative images of engineering seem often to outweigh the positives – breached levees in Hurricane Katrina, the rebuilding of Iraq, collapsing bridges and defective appliances. To be sure, we can also appreciate the internet, iPhones, a succession of jet liners that succeeded from the beginning, and so on. But it is not easy to attach names to most of these advancements (nor, for that matter, to the failures).

Recommendations to lighten the load, to decrease or rearrange the technical courses, and to increase the liberal arts components of the curriculum, may address some of these issues. Enhancing the experience and increasing the fun of engineering through early experiences with authentic projects would likewise increase the engagement in significant ways. The resulting sense of fulfillment and learning would lead to a greater sense of self-respect. But serious challenges stand in the way of implementing such changes within the undergraduate experience, quite apart from proposals to expand the engineering degree to include or require post-graduate experiences, valuable as those might be. One challenge is inertia; universities often stand on tradition. A second and related challenge is the demand that changes in curriculum and instructional practices would place on the faculty. Finally, for every course or activity that is added to the course of study, something has to be subtracted; time is limited.

Educating the Engineer of 2020 focuses more on the goal of fostering a broad liberal arts experience in undergraduate engineering. Achieving this aim would produce engineers capable of effective local leadership, able to serve as responsible designers and builders, sensitive to the implications of their work, and competent at communicating within their communities. The recommendations in this report are actually more daunting than Galloway's proposal, because the aim is to influence the entire field, and to engage faculties in this endeavor. Similar recommendations have been on the docket for almost a century, as noted by Wickenden (1927): "What appears to be most needed is an enriched conception of engineering and its place in the social economy, a broader grounding in its principles and methods, and a more general postponement of specialized training to graduate schools and to the stage of introductory experience which marks the transition to active life" (p. 125). As things now stand, however, engineering education in 2020 seems likely to resemble engineering education in 1920.

The volumes do point to two issues of potential importance for the future of undergraduate engineering in the United States: introduction of engineering into the K-12 curriculum, and inclusion of project-based activities early in the undergraduate experience. High school science courses have the potential to build an awareness of the field of engineering. Under *No Child Left Behind*, however, science has not been a high priority, and the basic mathematical skills that are tested are a far cry from the advanced and applied mathematics needed for both science and engineering. As noted by Battacharjee (2006), K-12 science is more likely to cover "flowers and rocks" than "planes and power plants..., how a volcano works but not how a car works" (p. 1237).

Readers might think that engineering concepts and activities are beyond the reach of K-12 students, but vocational education covered these topics in earlier times, and Massachusetts has developed a K-12 engineering curriculum that is remarkably true to the field, and that has survived *No Child Left Behind* as of this writing (2009). However, unless a parent, relative, or other acquaintance is an engineer, and is willing and able to talk about the profession, most high school graduates leave with little sense of who engineers are and what they do.

A Closer Look at the Learning Environment

These volumes address significant issues, but they take big-picture approaches. The day-to-day tasks confronting undergraduates in their courses pose challenges that are little changed over the century. To be sure, computers are available to handle many routine tasks, with consequent gains in efficiency and in the reach and complexity of tasks. But lecture/lab/homework remain the staples of the early courses. For example, Merriam's *Statics* (Meriam & Kraige, 2007) is now in its sixth edition, but the first edition published in 1951 would be familiar to today's students.

Much has been learned over the decades about curriculum, instruction, and learning. Some findings amount to refinements on old themes: the importance of practice with feedback, the value of discussion and dialogue, and the essentiality of transfer. Other topics are genuinely new in the past fifty years: the critical role of cognitive organization, the concept of metacognition, and the various ways in which motivation undergirds learning (Bransford, et al., 1999). Many of these ideas have appeared in the *Journal of Engineering Education*, and a useful compilation can be found in Wankat and Oreovicz (1995). Perhaps the most valuable segment of the latter book is the comparison between novice and expert (p. 69) – the goal of most engineering curricula is to lead the student along the path from the former to the latter.

The novice-expert contrast has been closely examined in recent years (Ericsson,et al, 2006): Novices tend to look on the surface, while experts quickly grasp the more fundamental elements of a problem. Experts spend time thinking about where they want to wind up, whereas novices start moving right away. Experts are flexible; novices pick a plan and stick with it. These characteristics apply to many arenas of complex learning. The challenge is to help novices move effectively and efficiently toward expertise. Curiously, the literatures on learning and expertise are seldom linked. For instance, acquiring expertise surely requires practice with feedback. But what kind of practice, and with what feedback? Practice makes permanent, but if the exercises focus on a linear rote sequence of disconnected objectives, students may not acquire the metacognitive conceptual knowledge that facilitates learning and transfer. Feedback can inform the student about mistakes (and successes), but this information may not promote learning, and may actually prove discouraging. If delayed following a lengthy exercise, feedback may not point the student to the critical junctures where he or she made a wrong turn.

In the remainder of this section, we discuss a matter not covered in the volumes: increasing the effectiveness and efficiency of existing coursework. We will use, as an example, rigid body mechanics, a virtually universal requirement in the undergraduate curriculum, and a challenge for many students. This domain is comprised of two primary sub-domains, *statics*, the study of bodies in equilibrium under the action of forces, and *dynamics*, which concerns the motion of bodies. Mechanics relies on both physics and mathematics. Instruction (both lectures and textbooks) relies largely on practice exercises comprised of real-world problems presented with text and graphics. In one example, for instance, a "jaws-of-life" device is shown being used to pry apart wreckage and free an accident victim. The text directs the student to "determine the vertical force *R* which is exerted by the jaw tips on the wreckage" (Meriam & Kraige, 2007, p. 212). The picture and text provide essential parameters: the dimensions of the device and the pressure applied to the actuating piston.

Textbook problems are actually mini-projects. The previous example is among the simpler problems in this section of the textbook. Other problems include an automotive floor jack, a cherry picker, an aircraft landing gear, an excavator, and so on. While these problems are paper drawings rather than realia, and parameters are included rather than requiring the student to perform measurements, these exercises offer students experiences akin to those they might encounter on the job.

In solving a typical statics problem, the student's task is to create a sketch – the free body diagram – that identifies the object or objects of interest and then indicates the forces at work on them. The student next uses this diagram to construct a system of equations to determine the unknowns. Many students, even those who have done well in physics and advanced math (including calculus), are often stymied by these tasks. The difficulty seems partly perceptual. For a complex (and hence realistic) figure, what objects should be included in the free body diagram and what forces are at work where?

Students work through many examples during a statics course, but typically receive scant advice about perceptual strategies for extracting the underlying structure of complex problems. Meriam & Kraige (2007) offer a page early in the book on graphic analyses with advice about this topic: (1) representing a physical system with sketches and diagrams helps with interpretation; (2) graphical solutions are often easier than direct mathematical solutions; and (3) charts and graphs are useful for presenting the results of an analysis. In applying the principles of mechanics, the student is instructed to "*isolate* the body in question from all other bodies… This *isolation* should exist mentally and should be represented on paper. The diagram of such an isolated body with *all* external forces acting *on* it is called a *free body diagram*." (p. 16). This advice seems on target, but for students the challenge is how to follow it, and for instructors, the challenge is how to guide students in the acquisition of the complex perceptual and cognitive strategies entailed in the advice. The process may be obvious to the instructor, but students may not see it. The task of constructing free body diagrams illustrates the difficulty of teaching for transfer. The student may follow the reasoning for the "jaws-of-life," but how does this learning apply to a floor jack?

In our research, we have been exploring a novel approach to guiding students through this kind of problem-solving. The Newton's Pen system (Lee, et al., 2008) is a pen-based tutoring system for an Anoto-based pentop computer (we used the LeapFrog FLY). A pentop is a pen with an embedded computer processor and camera. The camera works in conjunction with special dot-printed paper to digitize the user's pen strokes. Newton's Pen can interpret free body diagrams and handwritten equations, and provides context-sensitive tutorial feedback in response to problem-solving errors and taps on a Help button. Newton's Pen employs a tutorial strategy based on the concept of worked-through examples, in which students are introduced to a topic via the process of reconstructing a provided solution to a problem. This approach is distinct from the notion of worked-out examples (McNeill, Lizotte, Krajcik, & Marx, 2006) in which students begin by examining a provided solution.

In our studies of the usability and instructional efficacy of Newton's Pen, students first completed a pre-assessment problem to assess their initial ability to solve a statics problem, including constructing free body diagrams and equilibrium equations. Most students in our studies encountered considerable difficulty with this exercise (our studies to date have focused on students studying statics in an introductory undergraduate physics course). Students were then presented with a new, solved problem. Newton's Pen provided step-by-step instructions, guiding the student in reconstructing the provided solution. Although the task might seem simply to copy the solution, students typically attempted to understand the relationships among its various parts. Whenever a student made a mistake, or tapped Help, the pen responded instantly with tiered (scaffolded) reactions, such as: (1) "draw the forces," (2) "draw force 'W'," (3) "draw an arrow pointing down." After working through the example solution, students were then presented with yet another problem, this time without a solution. Students solved this problem using the tutorial support as needed.

Our findings thus far are promising, though necessarily tentative. At the end an hour-long session, virtually all students, when again presented the pre-assessment problem, solved it quickly and with confidence. One participant summarized the experience by remarking that "It's almost like having the professor in your hand" – a more encouraging portrayal of "professor" than we would have predicted.

The preceding example complements the message from the volumes covered in this review. The aspirations expressed in the various reports merit serious attention, now as they did a century ago, for administrators and faculty, for policy makers, and (especially as regards the K-12 proposals) for the public at large. Our point is that fundamental enhancements in basic instruction in engineering education where the rubber hits the road (or the pen hits the paper) are also essential ingredients for realizing the mega-reforms laid out in the volumes. The United States continues to provide leadership in the development of innovative concepts and products. The iPhone originated in this country, and it is likely that solutions to global warming, more efficient transportation systems, handling the accumulation of trash, and a multitude of other sophisticated and mundane problems will emerge from leadership provided by this nation's engineers (and engineering faculties). We could clearly benefit from improvements in the preparation of the broad spectrum of engineering graduates including "idea makers" and those who translate ideas into products. Realizing these goals will ultimately depend upon the availability of young people from a diverse array of backgrounds and interests who discover the adventure of engineering expressed so passionately by Hoover at the end of his career in the earlier quote, and reframed recently by Bruce Alberts (editor of *Science*): engineering and science are essential to our society because (1) they instill a sense of optimism that "all problems are, in principle, solvable;" (2) they focus on "long term-consequences of current actions," and (3) "they emphasize discovering what works without reference to ideology" (Alberts, 2008, p. 649).

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