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KEYNOTE LECTURE

ARE ENGINEERS LOSING CONTROL OF TECHNOLOGY? From 'Problem Solving' to 'Problem Definition and Solution' in Engineering Education

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Educators in chemical engineering around the world are now working hard to re-imagine the field in response to rapid technological change. Real concern exists about the possible loss of cohesion and identity. The main responses focus on restructuring its engineering science core. This concern and attendant strategies are also found in other engineering fields. Might rapid technological change be posing a fundamental challenge to the jurisdiction of engineering work? This analysis reviews the engineering emphasis in different countries on technical problem solving and outlines four contemporary challenges to the corollary claim of control over technological innovation. Responding to these challenges may require abandoning the goal of broadening engineering education, for they indicate not that technical education in engineering is too narrow but may be incomplete. An alternative strategy for adjusting the jurisdiction of engineering work is to formally include the activity of problem definition. The analysis concludes by analysing four characteristics of a model of engineering as Problem Definition and Solution and outlining three types of strategies for integrating problem definition into engineering education.

Keywords: engineering education; engineering profession; problem solving; problem definition.

INTRODUCTION

Educators in chemical engineering around the world are now working hard to re-imagine the field in response to rapid technological change. The perceived need for change is marked and justified especially by the emergence and importance attributed to biotechnology, information technology, and nanotechnology. A key motivation for reform in chemical engineering curricula is that the majority of graduating chemical engineers now find employment in arenas other than commodity production in the petrochemical industry (Calabrese, 2004).

Real concern exists about the possible loss of cohesion and identity for the field and the profession (Grant and Dickson, 2002, cited in Molzahn, 2004). In 2001, the Working Party on Education (WPE) of the European Federation of Chemical Engineers reported fears that 'branching off specialist subjects from chemical engineering might lead to its eventual demise'. That is, '[n]ew branches, such as food engineering, pharmaceutical engineering, biochemical engineering, environmental engineering, fire engineering, etc., threaten ... to disrupt or dilute the basic curriculum or to divert potential chemical engineering students away from the mainstream discipline' (Gillett, 2001:563). The US-based Frontiers in Chemical Engineering Education group worries about dilution at the cutting edge: 'We need to have a clear vision of chemical engineering in order to function effectively in multidisciplinary research' (Frontiers, 2003:12). Concerns for chemical engineering education typically revolve around such core knowledge questions as 'How far will [curricula] further be based on the classical unit operations approach? What about the basics?' as well as 'Is chemical engineering changing into a computer science? ... [D]oes it need more product orientation? What about bio-process engineering?' (Molzahn, 2004:1530).

To date, the main strategies for redefining the discipline in response to technological change consist of rethinking and revising its engineering science core. The search is on for a definable region of abstract academic knowledge that would renew the discipline's distinctive identity and enable it to persist in a rapidly changing environment. Not surprisingly, much disagreement exists about the optimal pathway. For some, the principal need is to revise

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existing textbooks to consider applications that integrate molecular science (Calabrese, 2004). Others search for a 'third paradigm' that would take its place alongside unit operations and transport systems as a central, unifying theoretical framework (Ottino, 2001). Still others advocate a fundamental restructuring of chemical engineering curricula around such concepts as molecular processes, multi-scale analysis, and systems analysis and synthesis (Frontiers, 2003). For all, the central problem, the WPE put it, involves 'how to adapt the discipline to meet technological and societal changes without losing its identity' (Gillett, 2001:561).

This concern about a loss of disciplinary cohesion and identity is shared widely across fields of engineering. Chemical engineers may feel themselves especially vulnerable but the yearning for a revised engineering science core does not distinguish chemical engineering from other engineering fields. New specialties are rapidly emerging not only across the Big Four (chemical, civil, electrical, and mechanical) but in other, younger fields as well.

Might it be the case that rapid technological change is posing a fundamental challenge to engineering in general? Could it be revealing an inherent vulnerability in the disciplinary identities of engineering fields, namely their claimed identification with technological development? Might engineers no longer be able to legitimize their fields easily and wholly in terms of contributions to technological innovation? Put most bluntly, are engineers losing control of technology?

Because these questions have potentially far-reaching implications, it is worthwhile to consider some of the relevant evidence. The discussion below begins by briefly reviewing the strong core emphasis in fields of engineering on technological development and technical problem solving. The identity of 'problem solver' labelled a distinctive strength of engineers as long as others did not challenge it. However, in response to an acceleration of technological change, other fields and professions are now laying claim to technological development as a significant component of their work. In this context, a collection of disciplines that explicitly limit their role to the solving of technical problems risks a serious reduction in the status and value of their work. Can engineers claim to be unique when others do technology too?

The analysis proceeds by identifying and outlining the features of four contemporary challenges to the engineering claim of control over technological innovation. These challenges complement one another by affecting the definition of engineering work in different ways. A review of them forces more direct attention to the question: Is the emphasis in engineering on technical problem solving a sufficient representation of engineering work? Furthermore, might the general understanding of engineering as technical problem solving exacerbate, or actually function as a key source of, several vexed problems in contemporary engineering education?

At this point the analysis turns to speculation, hopefully informed, suggesting that successfully responding to the array of contemporary challenges may require abandoning the oft-stated goal of 'broadening' engineering education. To focus on broadening may be to lose the battle at the outset because it preserves a distinction between technical core and non-technical periphery. If successful engineering practice has always involved more than technical problem solving, then the important point is not that technical education in engineering has been narrow but that it has been incomplete. Accordingly, the challenge today is not to broaden it but to rethink and redefine its core.

THE ENGINEER AS TECHNICAL PROBLEM SOLVER

The Bologna process in Europe has made evident significant differences in national systems of engineering education (Molzahn, 2004; Yeargan and Hernaut, 2001). Indeed, comparative historical research on engineering education reveals that what has counted as engineers and engineering knowledge has varied greatly over time and from place to place (e.g., Downey and Lucena, 2004; Kranakis, 1997; Meiksins and Smith, 1996). At the same time, however, a key commonality within and across national boundaries has been a widespread commitment to and felt responsibility for technological development. While the precise character of such commitments and their implications for engineers' careers and engineering work have varied from place to place, these have typically been defined in exclusively technical terms. Consider some brief illustrations.

In France, the elite *grandes écoles* have long functioned as the standard against which all French engineering education has been measured (Alder, 1997; Kranakis, 1997; Crawford, 1996). In these schools, the commitment to technological development has been formulated primarily in terms of mathematical theory in the engineering sciences and the derivation of applications from first principles. The most successful graduates have typically moved directly into the French administration where their work has effectively defined the national interest and where highest valued has been placed on technologies that advance social order, especially transportation, communications, and energy technologies (Crawford, 1989; Hecht, 1998). Moving downward in the ranking of schools, one finds, across time, increasing numbers, increasing attention to practical training, and increasing employment in subordinate government positions and in private industry. Indeed, as the French historian of engineering André Grelon reports (2004, private communication), by as early as 1900 fewer than half of graduate French engineers worked in government.

Over the past two decades, French engineering educators and administrators have been working to accommodate the rising status of engineering work in the private sector. As such, they are facing new questions about what engineers should know to be successful. At the same time, however, the *grandes écoles* and the career pathways they produce remain at the top of the French occupational hierarchy (Barsoux, 1989), along with the dominant image of engineering problem solving as applied science. It remains significant that the huge military parade in Paris each July celebrating the accomplishments of the Republic is led by second-year students from the École Polytechnique, the most elite of the schools.

In Germany, the two-tiered system of engineering education first emerged and expanded during the late-nineteenth century (Gispen, 1988, 1990, 1996). This evolution was linked to the parallel emergence and increasing emphasis on quality technics as a site and vehicle for the emancipation of German *geist* (a combination of mind and spirit thought to be shared by all properly German people) (Manegold, 1978; Herf, 1984). As such, the development of quality technics, a term that refers to both the products and the process of technical work, became a key metric of national progress (Downey and Lucena, 2004). What eventually became the technical universities originally drew their justification by contributing to the development of reason, which had achieved legitimacy in the early-19th century as a pathway for emancipating *geist.* The institutions that became the *fachochschulen* were slowly able to demonstrate that the production of quality technics in any context, including the private as well as the public sector, could be contributors to German progress. German engineering gained national significance as both science-based and hands-on precision in technics, whether in military technologies, automobiles, or coffee makers, became a key marker of quality and key emphasis in engineering education.

In recent years, German engineers have been grappling with the challenge to maintain high quality while competing in a world increasingly defined by the low-cost production of goods for mass consumption (Legg, 1990). This change brings new challenges to German engineering education (Hernaut, 1994; Kennedy, 1996). But while German educators, especially at the *fachochschulen*, have taken a lead in Europe in adapting their systems to a workplace increasingly obsessed with cost reduction, they have not given up the primary focus on quality technics.

In the UK broadly construed, engineers have struggled for over two centuries to overcome a stigmatized association with manual labour and achieve high status as autonomous professionals who serve as the creative designers and developers of new technologies (Smith and Whalley, 1996). Emerging from the artisanal classes during the Industrial Revolution, engineers developed a distinctive focus on practical technical knowledge while using apprenticeship training to emulate the classical professions of law, medicine, and clergy (Buchanan, 1989). Working in a class structure that measured progress, privilege, and civilization in terms of distance from manual labour, engineering educators over time did succeed in establishing educational institutions with greater attention to the engineering sciences, but an exclusive focus on technical subjects and knowledge continued. Training in the engineering sciences supplemented the emphasis on practical technical knowledge, whose continuing value today is evidenced in such activities as job-shadowing, gap year placements, and the revised apprenticeship system. The contemporary, increasing requirement for industries to compete on the basis of low-cost, mass production may be introducing new considerations for engineering work but has not blunted the British emphasis on creativity in technological design and near-exclusive focus on technical knowledge.

Finally, the US offers a case of longstanding battles over the relationship between the technical and non-technical dimensions of engineering education. US engineering education became settled as school-based operations in the late-19th century, in a context in which national progress had come to be measured in terms of the private-sector production of low-cost goods for mass consumption (Reynolds, 1991; Hounshell, 1984; Misa, 1995). As engineering increasingly gained an association with mass industrial production, debates emerged over the 'narrowness' of engineering education and the relative proportions of curricular time that should be devoted to technical and non-technical subjects, with the latter always relegated to the margins in elective courses (Talbot, 1911; Williams, 2002). The American response to Sputnik in the 1960s and 1970s had the effect of redefining the technical core in terms of the emergent engineering sciences. What came to be known as engineering design became a downstream application of science-based problem solving and everything else, including 'broadening' education in the liberal arts and professional training in 'soft skills' functioned as supplementary activities. Engineering practice during the Cold War came to consist both of continuing efforts to advance the system of mass industrial production and new science-based efforts to build military technologies in order to protect that system from the challenge of communism.

The main challenge of the past two decades has involved coping with the fact that a distinctively American commitment to low-cost, mass use has scaled up to become a worldwide phenomenon and that many other countries, especially in East Asia, have become successful in developing their own versions. The shock of this expansion and redefinition of the world in terms of economic competitiveness has prompted a massive re-evaluation of the balance of technical and non-technical experiences in engineering education.

This small and all-too-brief set of cases illustrates not only that significant national differences have existed in what has counted as engineers and been valued as engineering knowledge but also calls attention to a distinctive commonality in the engineering commitment to technological change and focus on technical problem solving, locally defined. As French engineers have contributed to social order by placing greatest emphasis on national technology systems, German engineers have emancipated national *geist* through high-quality products and precision machines, British engineers have enacted creative genius while specializing in batch production, and American engineers have worked to improve the material comfort of the masses through industrial production of low-cost goods. In each case engineers have measured their contributions primarily through technologies and defined their education as technical preparation for technological innovation.

The 2004 US National Academy of Engineering report *The Engineer of 2020: Visions of Engineering in the New Century* explicitly articulates a current version of the engineering vision of a fundamental link with technology and of the identity of engineers as technical problem solvers. The report's preface signals the importance it attributes to technology by informing readers that it builds on 'a steering committee consensus about new technologies that are likely to significantly influence the future course of engineering' (NAE, 2004:7). The report begins by asserting unambiguously that '[t]echnology is the outcome of engineering' (NAE, 2004:7), and it devotes the first chapter to detailing emerging technologies. Documenting emerging technologies is important because it has been 'through technology' that engineering 'ha[s] forged an irreversible imprint on our lives and our identity' (p.9). That is, it has been 'through its role in the creation and implementation of technology' that engineering 'has been a key force in the improvement of our economic well-being, health, and quality of life' (p.47).

In this image of a tight linkage between engineering and technology, engineers contribute as technical problem solvers by recognizing the technological, or engineering, content in societal problems and then solving the technological problem. 'Engineering is problem recognition, formulation, and solution', the *2020* report asserts (p.43). The field is important because it 'offers men and women an unparalleled opportunity to experience the joy of improving the quality of life for humankind through development of engineering solutions to societal problems' (p.48).

Crucial to this activity is the idea that engineers, as technological problem solvers, *respond* to calls from society, much as a consultant responds to clients. Thus, for example, in the face of an assortment of potential catastrophes, engineers in 2020 'will be asked to create solutions that minimize the risk of complete failure and ... prepare backup solutions that enable rapid recovery, reconstruction, and deployment' (p.24). Also, given changing demographics, these future engineers 'will need to develop solutions that are acceptable to an increasingly diverse population' (p.28). Or, green engineers will 'actively engage communities and stakeholders in the development of engineering solutions' (p.22), and grappling with the complexities of emerging technologies will require engineers to 'achieve interdisciplinary solutions to engineering problems' (p.24).

Perhaps the most important element in this consensus engineering view is the location of science away from technology, positioned upstream in the realm of unrestricted inquiry and discovery. 'It is rare', the *2020* report asserts, 'that science translates directly to technology, just as it is not true that engineering is just applied science'. Evidence from the past justifies the point: '[h]istorically, technological advances, such as the airplane, steam engine, and internal combustion engine, have occurred before the underlying science was developed to explain how they work' (p.7).

In sum, the *2020* report articulates what the comparative histories of engineering reveal: the identification with technological development and the professional identity of technical problem solver. In concluding an influential historical account of early French engineering, the historian Ken Alder (1997) asserts that '[E]ngineers have been designed to serve'. Crucially, engineers have defined this service as the provision of solutions to technological problems.

LOSS OF CONTROL OVER TECHNOLOGY

Might the acceleration of technological change that compels the attention not only of the steering committee for the *2020* report but also attendees at the 2005 World Congress of Chemical Engineers and recent contributors to *Chemical Engineering Research and Design* actually be a key factor undermining the link between technology and engineering that justifies this attention in the first place? The sociologist of professions Andrew Abbott provides a tool for investigating this possibility when he suggests that 'the evolution of professions ... results from their interrelations' (1988:8). That is, professions stand in relation to one another and compete with one another. This idea takes on special significance when he further points out that professions can be vulnerable to change through technological developments. 'Changes in technologies and organizations', he writes, 'provide most new professional tasks. Correlatively, the two are the central destroyers of professional work' (p.92). In his own work, Abbott shows how professions often respond to technological change by altering their claims of 'jurisdiction' over particular areas of work (p.20), and he traces evolving claims of jurisdiction while mapping expansions, contractions, emergences, and disappearances in professions ranging from nursing to law to social work. For our purposes, a key question to ask is whether or not new technologies are introducing disturbances whose effects include changing the relationships that define engineering.

Viewed in retrospect, fields of engineering have long enjoyed relative freedom from challenge to their claim to be creative sources of technological innovations and the collective home of people who develop technological solutions to societal problems. But it is just this freedom that should lead us to wonder what might happen if other professions and occupational groups began to claim jurisdiction over technological development. In an insightful and engaging account of recent institutional transformation at MIT, the historian of technology Rosalind Williams makes the case that engineering is now expanding in so many directions at once that it may, in fact, be disintegrating (Williams, 2002). Her analysis of this 'expansive disintegration' maps changes from the inside of engineering outward, and all engineers today can likely see themselves in her account. In order to call attention to potential challenges to engineering as well as to assess the implications of alternative potential responses that engineers might enact, it may be helpful to also map changes from the outside of engineering inward. Accordingly, we now turn to explore briefly four different types of contemporary challenges to the engineering claim of jurisdiction over technological innovation.

The first and seemingly most threatening set of challenges comes from significant changes in the work of scientists. The *2020* report's image of science as significantly upstream of technology was certainly defensible through the mid-20th century. As economic historians David Mowery and Nathan Rosenberg demonstrate in an extended analysis of the historical delay between discovery and application, 'technological exploitation of new scientific understanding often require[d] considerable time because of the need for additional applied research before the economically useful knowledge [could] be extracted from a new but abstract formulation' (1989:25). They explain that it would not be correct to say, in general, that science was 'loosely connected' to innovation because by the late-19th century technologies routinely emerged through the application of science. It was entirely correct, however, to assert that 'recent scientific research was loosely tied to innovation' (p.28). What we can draw from this is that when engineers were claiming jurisdiction over technology during the 18th, 19th, and much of the 20th centuries they were inserting their self-image into a real historical gap between the creation of new knowledge and its appearance in technologies.

But such is no longer the case. Much evidence exists of the turn toward technology among scientists, especially after the Cold War. One way to document this shift, for example, is to trace the expansion in the numbers and character of patents awarded to universities, the traditional centers for basic, unrestricted research. The US National Science Board reports in *Science and Engineering Indicators 2004* that '[p]atenting by academic institutions has markedly increased over the past three decades, rising from about 250–350 patents annually in the 1970s to more than 3200 patents in 2001' (NSB, 2004). The number of academic institutions receiving patents nearly tripled and the share of patents granted to them increased from 1.5% to 4%. Of critical importance here is the fact that this growth was centered not in engineering but 'occurred primarily in the life sciences and biotechnology'. Indeed, the class that experienced the fastest growth was chemistry, molecular biology, and microbiology.

Another indicator of a shift toward technology in the focus of scientific work lies in changes in the scope of funding for scientific research. For example, in the early 1980s the US National Science Foundation both acknowledged and contributed to an increasingly blurred distinction between basic and applied science when it stopped designating applied science as a separate funding category (Lucena, 1996). Also, in 1987 NSF introduced funding for multi-institutional, multidisciplinary 'Science and Technology Centers' with an aggressive economic goal of 'respon[ding] to rising global competition' by 'mount[ing] an innovative, interdisciplinary attack in important areas of basic research' (Graphics and Visualization Center, 2004). Through the 1990s and present decade, NSF dramatically increased the number of science programme that are linked directly to technological outputs, expanded research programme that encourage direct collaborations with industry, and rewrote virtually all science programme descriptions to include technological development as a desirable outcome alongside contributions to knowledge, education, and training. A more recent, highly significant change is a Foundation-wide requirement that all project summaries must demonstrate not only the 'intellectual merits' of the project but also its 'broader impacts', or the proposal 'will be returned without review'. One clear way to demonstrate broader impacts is to demonstrate the link between the research and potential new technologies.

The delay that Mowery and Rosenberg found was in a research world in which physics provided the model for scientific knowledge production. Disappearance of that delay is linked to the shift toward the life sciences and information technology, which has included a change in how scientists understand themselves. For example, on the one hand, the emergent and much-celebrated field of tissue engineering can be seen as an extension or expansion of chemical and mechanical engineering into the design and construction of biohybrid life forms (Hogle, 2003; Williams, 2002). But on the other hand, the interdisciplinary collaborations constituting the field among practitioners from biophysics, developmental biology, materials science, biochemistry, genomics, and several branches of medicine also demonstrate the increasing comfort that scientists have in associating themselves with a field that can be labeled with the word 'engineering'. Similarly, many cutting-edge nanoscientists do not judge themselves to have fully established their professional reputations until they have founded successful start-up companies (Baird and Shew, 2004).

The same level of comfort among scientists with an expanding association with technology and, hence, engineering can be found in the 2003 report of the US National Research Council's *Beyond the Molecular Frontier: Challenges for Chemistry and Chemical Engineering.* Strikingly, the report 'departs from the earlier practice of treating chemistry and chemical engineering as separate disciplines', instead lumping them together under the more general term 'chemical sciences'. The stated goal is to present 'the entire spectrum of activities in the chemical sciences', a spectrum that now includes not only 'research' and 'discovery' but also 'invention'. All this is justified, the report holds, by 'strong couplings' between chemists and chemical engineers in universities and industries (National Research Council, 2003:2). In short, invention and technological development no longer distinguish chemical engineering from chemistry, but in this case it is not the label 'engineering' that is being celebrated and extended.

A second source of challenge to the engineering claim of jurisdiction over technological innovation is the mass production of engineers trained only in the engineering sciences. In a 2004 interview, a senior engineering official and influential government consultant from Cairo University in Egypt complained that while the Faculty of Engineering judges itself to have a capacity of 4000 students, its enrollments typically exceed 15 000 students in any given semester. The education of these students is necessarily structured around large lectures and annual exams, with a focus on testing students' knowledge of relevant engineering sciences. The implications go far beyond Egypt, for the country has long been a major producer and exporter of engineering graduates to countries across the Middle East.

The *2020* report describes the 'rapidly improving educational capabilities in countries like China and India' and estimates that China alone is producing 'more than three times the graduates in all fields of engineering than is the United States' (p.33). At the 2004 annual meeting of the US National Academy of Engineering, NAE President William Wulf reported that 'new US engineers account for only about 7.5 percent of the world total' (Wulf, 2004). While the global implications of this development have several dimensions, for our purposes it demonstrates that countries such as China, India, Egypt, and Phillipines are already enacting a model for what engineers across the world may be becoming technical functionaries in support positions. I recently placed four telephone calls for technical support for my Palm Pilot. Two were answered in India, two in the Phillipines. All four technicians held bachelor's degrees in computer engineering.

The *2020* report describes two key features of this emergent model. These workers, it explains, are 'highly skilled ... with engineering and science backgrounds', and they are 'willing and able to work for wages well below those in the developed nations' (NAE, 2004:33). On the one hand, this situation is the product of a distinctively American export, an industrial system that seeks low-wage workers to fuel low-cost production for mass consumption. On the other hand, one implication is a reverse flow of influence in the jurisdiction of engineering, the successful demonstration of a model in which engineers are valued more for their work as technical problem solvers than as technology creators.

Williams points toward a third, related challenge to the professional identities of engineers when she asserts that '[a]ll engineering departments are becoming, in some form or other, to a greater or lesser extent, departments of applied-information technology' (2002:46). According to her, increasing reliance on a common digital language 'lifts engineering, once the most down-to-earth of professions from its familiar ground of materiality, endowing it with a ghostly lightness of being' (p.47). This dematerialization of engineering work pulls at least some engineers into a densely populated world of information technology workers, millions of whom have gained 'engineering' credentials by passing exams rather than completing curricula.

In the 2000 US Department of Education report *A Parallel Postsecondary Universe: The Certification System in Information Technology*, longtime education researcher Clifford Adelman maps out the contours of a system that between 1997 and 2000 produced over two million information technology certifications worldwide, while operating as an 'international guild' almost entirely outside of government-operated systems of data collection and accreditation. Armed with such titles as Accredited Systems Engineer (Compaq), Certified Novell Engineer, Microsoft Certified Systems Engineer and Red Hat Certified Engineer, students 'assemble valises of special knowledge and skills, apply them in different work-organization contexts, and modify them by (1) personal predilection, (2) personal perception of potential 'work-life' paths, and (3) labour market changes' (p.30). These new adaptive, flexible workers realize that 'work life mobility demands the transparent and portable evidence of a certification' (p.3). The challenge to universities is such that 'the demographic "tidal zone" [they] anticipate may turn into little more than a splash if students increasingly opt to participate in a system beyond our ken' (p.3). This challenge may not affect most engineers. But the easy use of the term 'engineer' in this context illustrates the potential risk of devaluation associated with defining the engineering profession as technical problem solving for clients.

Finally, a key source of challenge comes from a phenomenon that is often characterized as a site of promise and opportunity for engineers, the institutionalization of teamwork in industry. Through a succession of movements that have included total quality management, business process re-engineering, and, most recently, knowledge management, industrial organizations have worked to restructure themselves into flexible mazes of product and process development teams. Such teamwork increasingly puts engineers at the table with business managers, marketing and salespeople, researchers, labour representatives, information technology specialists, and so on. Since effective teamwork affords all participants some measure of responsibility over and, hence, identification with technological developments, the phenomenon makes it increasingly difficult for engineers to claim jurisdiction for themselves. Indeed, to the extent that engineers may be the participants most inclined to understand the problem at stake in exclusively technical terms, they might very well comprise the profession least likely to respond to such shared responsibilities in other than defensive terms. In other words, does becoming a good team member occur in spite of engineering training rather than because of it?

In sum, rapid technological change appears to make visible a unique vulnerability in engineers' identification with technological development and dominant understanding of themselves as technical problem solvers. By claiming jurisdiction only over the solving of technological problems, engineering has positioned itself as society's technological consultant, there to help but only when asked. The engineering claim to creativity in technological development is now contested directly by both research scientists and teammates in industry. Also, the potential demoting of engineering into technical support may be modelled by the mass production of engineers in poorer countries and easy appropriation of the label by those who certify engineers with a single exam. In this context, for engineering fields such as chemical engineering to cope with technological change by placing highest priority on clarifying and redefining the science-based problem solving at their core just may be to misdiagnose and fail to respond adequately to the core challenge.

ENGINEERING AS 'PROBLEM DEFINITION AND SOLUTION'

The main task facing engineering education in the present is to re-imagine and re-theorize its obligatory core and, hence, the essential heart of engineering identities. A key prerequisite to taking such a step is to move beyond a geometry of 'narrowness' and 'breadth'. In the first place, the critique of narrowness in engineering education has a long history without resolution. MIT professor Henry Talbot was writing in 1911 when he offered a thoughtful defense of the engineering curriculum against 'the general charge of "narrowness" and inadequacy which is directed against our courses' (Talbot, 1911:118). But the main problem with the critique of narrowness is that it necessarily points toward breadth as its solution. As Williams explains, for example, the 1949 Lewis Report at MIT, authored by Warren K Lewis, a founder of chemical engineering and her grandfather, labelled its central recommendation 'A Broader Educational Mission' and asserted 'we recognize especially a need to develop a broader type of professional training that will fit engineers to assume places of leadership in modern society ...' (2002:67). Likewise, the *2020* report calls for engineers 'who are broadly educated, who see themselves as global citizens, who can be leaders in business and public services, and who are ethically grounded' (2004:5). Between these two reports are hundreds of other examples.

The broadly-trained engineer is indeed an attractive image. One can make a plausible case that broadening the training of engineers could help engineering education address several vexed problems, including ameliorating European difficulties in attracting quality students, US difficulties in recruiting and retaining women and underrepresented minorities, the general invisibility of engineering professions and lack of public understanding of what engineers do, and, particular to Europe, difficulties in contributing affirmatively and collectively to the Bologna process.

However, the image of breadth is problematic because it tends to preserve a distinction between core and periphery, with technical problem solving at the core and everything else at the periphery. Figure 1 offers a current example of

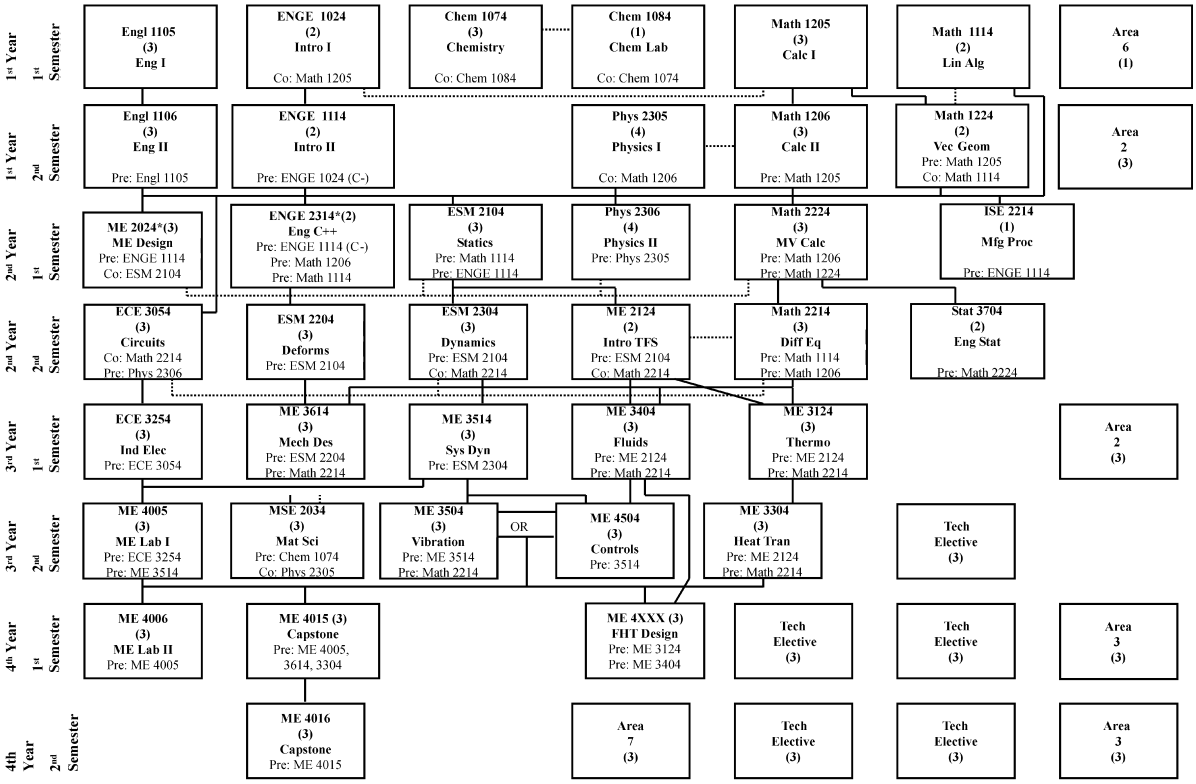

Figure 1. Proposed degree path sheet—ME Class of 2008.

how this works. The diagram is a flowchart of a US mechanical engineering curriculum distributed to students to guide them in course selection. Similar diagrams could be constructed of chemical engineering programmes. The key feature of the diagram is the array of vertical and horizontal lines that constitute the core of the curriculum in an interlocking network of prerequisites and co-requisites. Sitting directly above them are important preparatory experiences in the basic sciences. However, the main broadening experiences, elective courses in the humanities and social sciences ('areas' 2 and 3), sit off to the side on the right, connected neither to one another nor to anything else.

In the vast majority of engineering curricula, breadth is supplementary. While a given field can reasonably legislate its technical core, it cannot do so with breadth, which students achieve through mixes of classes they select at will and integrate, or not, on their own according to their own preferences and sensibilities. The image of breadth lacks a consistent vision. Hence, discussions about how to overcome narrowness tend to devolve into arguments over the appropriate distribution of credits between the required core and elected peripheries. For engineers whose passions and identities are defined by the technical core, the prospect of whittling away at core credits risks eroding the quality of engineering education and even transforming it into something entirely different.

In a move with dramatic implications, the US Accreditation Board for Engineering and Technology in 2000 shifted the locus of integration among the technical and non-technical dimensions of engineering education from credits on the student's transcript to the students themselves, as specifications of learning outcomes. Engineering Criteria 2000 has greatly energized the US engineering education community. What started in the 1990s as significantly increased attention to design and information technology (Downey and Lucena, 2003) now includes explosions of curricular interests in professional ethics, oral and written communication, teamwork, international experiences, continuing education, and so on, as well as the legitimation of research on engineering education (see the January 2005 issue of the *Journal of Engineering Education*).

The long-term success of this enterprise depends upon leaving behind the critique of narrowness and its call for breadth. One reason is that it is important to recognize that technical education in chemical engineering and other engineering fields is already broad and multidisciplinary. This commitment to technical breadth is the reason why each engineering field is defined not as a discipline but a collection of disciplines, as well as why responding to rapidly emerging technologies generates both excitement and anxiety.

A second reason is that the engineering image of problem solving is not just too narrow a label for engineering work; it is incomplete. It constitutes an insufficient description. Engineering problems do not solve themselves. They are always solved by people. As soon as one introduces people into problem solving, the process takes on human as well as technical dimensions. In focusing only on the technical dimensions of the process, engineering education abstracts out the human dimensions, defining these as extraneous and irrelevant. While this act of jurisdictional purification was wholly defensible, and perhaps even advisable given the rigour of mathematics, as long as other professions did not compete for the same work, it is no longer. What is needed now to respond to growing challenges to the jurisdiction of engineering work is a more accurate and complete label, one that might offer a framework that both encourages and guides the panoply of innovations currently taking place in engineering education, while also legitimizing these innovations as affirmations of engineering rather than efforts to transform it into something else. The *2020* report points in this direction when it observes, 'In many ways the roles that engineers take on have always extended beyond the realm of science and technology' (2004:37).

One way of acknowledging the core human dimensions of engineering work is to recognize that engineering problem solving has always included the activity of problem definition. In carrying out their work, engineers necessarily negotiate and re-negotiate the definitions of technological problems both among themselves and with non-engineers. Accordingly, one potentially promising way of remapping the jurisdiction of engineering work to adapt effectively to the challenges of the present may be to redefine engineering work in terms of both problem solving and problem definition.

A model of engineering as Problem Definition and Solution (PDS) would have at least four key characteristics. To illustrate these, consider an extrapolation of a well-argued case analysis from Moggridge and Cussler's (2000) important discussion of how to build chemical product design into chemical engineering curricula. The case involves a hypothetical printing company grappling with a pollution problem from a lithographic ink that contains the carcinogenic solvent methylene chloride (CH_2Cl_2). This solvent is also used in the cleaning process. By entering the air through evaporation, the solvent poses health risks to workers and the company risks censure from environmental regulators.

Focusing on product design, the chemical engineers involved proceed systematically through a procedure that includes (1) identifying needs, (2) generating ideas, (3) rationally selecting among available ideas, and (4) identifying how to put solutions into operation, including building and testing prototypes and estimating costs. The procedure is innovative because it explicitly pushes chemical engineers beyond the purely technical decisions that are typical in conventional models of process design, e.g., batch versus continuous processes, inputs and outputs, reactors and recycles, and separations and heat integration. Also, even though 'obviously a major simplification' (p.8), the design procedure differs from business management models of product development by insisting that technical knowledge is crucial to sound decision making.

In the hypothetical case, following the procedure yields the short-term solution of substituting the solvent toluene for methylene chloride, for toluene has a similar solubility parameter, is inexpensive, and although 'still toxic' has not banned by environmental authorities. The longer-term solution that appears most desirable is to change the resin chemistry to make the ink solvent-free but water soluble through a chemical trigger.

The first characteristic of a PDS model of engineering is that engineers involved in technology development would always expect to participate in activities of problem definition and, equally importantly, would be expected by others to participate in problem definition. In this design case, the process begins with the pollution problem clearly defined and focuses on translating it into engineering terms in order to provide solutions.

Implementing a PDS model would focus the engineers' attention much earlier, before the problem has been defined clearly. Issues involving emissions and health hazards are notoriously unclear and contested. Who decides initially that methylene chloride poses a danger, through what mechanisms, and at what concentrations? Is this knowledge developed outside the company, appearing through a list of hazardous chemicals published by the environmental authority? PDS engineers committed to successful problem definition would possess knowledge about what the environmental authority is, how it makes its decisions, and how methylene chloride showed up on its radar screen. Or perhaps the issue emerges through complaints from workers. PDS engineers would have knowledge about what workers know about the relevant production and cleaning processes, what are their customary work practices, and what has been the history of relationships among workers, between workers and management, and so on. Or perhaps someone from management quietly expresses a concern about the future of the cheque-printing business. PDS engineers would have knowledge of various management positions gained by learning about the distinct responsibilities of company managers and the competing visions of the company's past, present, and future that live in management circles.

The key point here is that engineers trained to include both problem solving and problem definition in their work would involve themselves early in processes of problem solving, prior to the point at which a clear design problem emerges. These engineers would participate by bringing to bear valuable technical knowledge about chemical process and product development and manufacturing but also substantial knowledge of the nontechnical dimensions of those processes. As PDS engineers, they would include in their work exercises in mapping the positions, interests, and visions of all those groups who have stakes in the industrial processes of the company. Indeed, PDS engineers would be the only participants who expected and were expected by others to explicitly address both the technical and nontechnical dimensions of the processes at the same time.

A second characteristic of the PDS model is that problem definition involves collaborative work among people who define problems differently than one another. Engineers trained in conventional problem solving know that the first step in solving an engineering problem is to draw a boundary around it so that it can be analysed in mathematical terms (Downey and Lucena, 1997). Equally important is the fact that by successfully defining a problem one also takes possession of it, gaining control over what will count as desirable solutions. Instruction in the mathematical dimensions alone extracts engineers from this real-world condition, enabling them to pursue sound technical solutions to the problem as defined but only by also transporting them into an idealized mathematical space free of human difference and conflict. As such, it provides engineers with no strategies for solving problems when people disagree with one another about how to define the problem in the first place.

In the cheque-printing case, the chemical engineers take an important step by involving other people in the design process. They identify needs by interviewing management, workers, and the company's environmental consultants and health and safety administrators, and they generate ideas by meeting with expert consultants, analysing the experiences of competitors, and organizing brainstorming meetings. As PDS engineers, their work in interviewing stakeholders would include the additional responsibility to learn and explicitly map how all stakeholders understand the problem, what addressing the issue appears to mean to their future positions and identities, and how they understand their responsibilities. PDS engineers would investigate the history of the relationship between the company and the regulatory authority, knowing if such relations have been positive or not. They would examine the evolution of relationships among managers, engineers, and affected workers. They would find out if workers were worried about their jobs and trusted engineers and management sufficiently to participate in problem-solving experiences. PDS engineers would learn which managers might fear potential loss of the cheque-printing business and which might see it as a step forward for the company and for themselves.

Creative participation in collaborative problem definition thus includes but extends beyond figuring out how to translate a societal problem into a design problem for the engineering sciences. It can include but also extends beyond the use of systems analyses to link some economic and social dimensions to the technical problem solving process. The key work in collaborative problem definition involves the investigation of other perspectives. Its success depends upon the knowledge that one occupies only one point of view among many in the process of technological development and that disagreement is likely, even to the extent that agreement about a single definition of the problem may not be possible. PSD engineers would be important contributors to the collaborative definition of technical problems not only because their technical knowledge would enable them to understand the technical issues at stake but also because they would strive to understand these technical issues from different points of view and recognize the limitations of their own perspectives.

The third characteristic of the PDS model is that the process of generating technical solutions includes the non-technical work of assessing the implications of alternative solutions for stakeholders. Such work includes anticipating the possibility that engineers may not possess the knowledge crucial to the most desirable solutions. In the cheque-printing case, for example, the short-term solution of substituting toluene for methylene chloride works because it has a similar solubility parameter, is inexpensive, and is not banned by environmental authorities. However, it is still toxic. Engineers who defined their work as problem definition and solution would include in their jurisdiction responsibility for analysing from workers' points of view the implications of substituting a still toxic solvent for the one that has been banned. Would participating workers interpret this option as evidence that engineers are siding with management against them? If so, would they deem this to be an exceptional case or part of a longer-standing pattern? Would workers agree that substituting a different solvent is preferable to shutting down the cheque-printing process? What steps might be taken to mitigate these effects? Finally, might attending directly to workers' concerns lead to deliberation over solutions that fall outside of chemical engineering, e.g., introducing breathing apparatus to protect workers from either solvent or even building a room for the presses in which gaseous methylene chloride could be collected, concentrated, and disposed of through other means? PDS engineers would accept responsibility for exploring similar questions with each class of stakeholder.

Solving technological problems typically changes the relationships among participants in one way or another. Where one participant may gain additional contacts, status, and/or power, another participant may lose contacts, status, and/or power. Participants tend to weigh alternative solutions in both purely technical terms and in terms of the implications these solutions have for their identities. Indeed, in a given situation, the non-technical dimensions of the process may be not only significant but also a key determinant of a desirable outcome. Rather than avoiding such dimensions or rejecting them as politics that falls outside of engineering, PDS-trained engineers would know that technological problem solving always includes such non-technical dimensions and would draw on their training to find ways of dealing with both at the same time.

The fourth characteristic of the PDS model is that successful engineering work exercises leadership through technical mediation. Technical mediation has, once again, both technical and non-technical dimensions. In conventional definitions of engineering work, engineers have to make difficult trade-offs among alternative needs or design specifications. In the PDS model, engineers also have to make difficult trade-offs among alternative stakeholders, alternative definitions of the problem, and alternative perspectives about what is taking place, including their own. By defining the human dimension of engineering solutions as, minimally, mediating among the positions of stakeholders, whether between the company and regulatory agency, between workers and management, among workers, among managers, and so on, engineers continue to select solutions to meet technical needs but also to reconcile differences. Technical mediation is not a search for consensus judgments, which are often not attainable. Rather the process takes into account the fact that final decisions will affect the next round of decision making, for technical deliberations necessarily begin with the outcomes of previous deliberations. Reconciling differences as much as possible maximizes the possibility that the process is easier next time around.

Technical mediation by PDS engineers would still be engineering work. Most importantly, it would differ from the business management of people or knowledge management of a firm in that the scope of its vision would continue to extend beyond the identity of the firm. The cheque-printing case illustrates the separation of engineering identities from the company. For example, the product design engineers discard the idea of changing the presses because 'the company does not want to make the enormous capital investment involved' (Moggridge and Cussler, 2000:10). Also, if electronic data processing replaces hand-written cheques, 'the company may decide that ... printing cheques is like making buggy whips' (p.10). PDS engineers would fully understand and honor their responsibilities as employees, but the jurisdiction of their actual work would, by definition, leave open the boundaries that defined stakeholders, recognizing that these take shape in each case. Engineers would bear a continuing professional responsibility to juxtapose employer considerations with considerations of society at large.

When the engineering profession positions itself as only a provider of solutions waiting for society to ask it for help or give it problems to solve, it fails to fulfill its responsibility to bring its technical knowledge to bear in the definition of problems in the first place, and it also deprives society of the opportunity to look to engineers for leadership in problem definition. The *2020* report pictures engineering 'strengthen[ing] its leadership role in society' and envisions engineers working 'as leaders who serve in industry, government, education, and nonprofit organizations' (2004:48). But visible leadership for the engineering profession need not come only through technical genius and technological heroism. Indeed, it may be more likely to come from the hard work of including problem definition within its jurisdiction as a core competence and responsibility.

INTEGRATING PROBLEM DEFINITION INTO ENGINEERING EDUCATION

The key criterion for identifying and assessing pedagogical strategies to integrate problem definition into engineering education is to ask: how does this learning activity prepare engineering students to work with people who define problems differently than they do? In any policy-making process, movements toward a desired state of being must always start 'here', in the present and at this location. At present, engineering curricula everywhere tend to include a technical core and non-technical periphery. Accordingly, the distinctive challenge in the work of integrating problem definition into engineering education is to locate and champion both technical and non-technical bodies of knowledge at the core, especially education in the engineering sciences. The efforts required include three categories of initiatives: (1) adapting pedagogies in engineering science courses to emphasize the limitations of the knowledge they convey along with their strengths; (2) adapting pedagogies in peripheral courses to translate their forms of knowledge and modes of analysis in ways that engage the practical reasoning in technical problem solving while promising to help engineers understand and engage diverse technical perspectives on the job; and (3) adapting engineering curricula in ways that legitimize and encourage becoming more than one thing, i.e., more than one type of technical professional.

(1) How can one teach engineering science courses so that students come to understand what they are not learning? The main challenge to a PDS instructor or PDS textbook author is to teach not only the main mechanisms of analysis but also their boundaries. In *Designing Engineers*, the MIT engineer Louis Bucciarelli offers a helpful tool for addressing this issue with the concept 'object worlds'. Bucciarelli's point is that each engineering science creates and lives in one or more object worlds that engineers must enter into to do their analyses. The mathematical objects in these worlds are both crucial to quality engineering work and a significant source of difference and disagreement among engineers.

'In the simplest terms', Bucciarelli writes, 'design is the intersection of object worlds' (1994:20). Systematically examining three design projects that experienced high levels of uncertainty, Bucciarelli finds that '[t]he apparent incoherence and uncertainty of the process[es] ... derives in large measure from the differing interests and viewpoints of different parties to the design' (p.51). He observes how engineers and other professionals working within different object worlds 'will construct different stories according to their responsibilities and ... technical, professional interests' (p.71). As a result, because 'the authors of these stories display full confidence in their construction' (p.72), the key issue in defining the engineering problem at stake is not overcoming uncertainty but reconciling different perspectives.

Without overemphasizing the concept of object worlds, which some engineering faculty may find too ethereal, engineering science courses could be adapted systematically to present their material as introductions to abstract mathematical arenas that only partly overlap with one another. Engineering sciences from thermodynamics to heat transfer build ideal mathematical arenas that are useful and, indeed, beautiful, each of which posits a unique configuration of theoretical entities and processes. Engineering science faculty who commit their careers to advancing and improving the abstractions that constitute these arenas often build powerful personal commitments to their promise and value, which includes understanding their boundaries and relations to abstractions in other such arenas. To gain a pedagogical responsibility not only to deliver the mechanisms to students but also to help students learn to articulate the value of those mechanisms and how they are distinct from other mechanisms could very well provide faculty with welcome opportunities to share both their knowledge and their passions.

Given the currently dominant structure of engineering science courses as lectures, problem sets, and exams, the faculty involved in, for example, a chemical engineering thermodynamics class would have to be creative in addressing such questions as: What are the key entities and processes in this thermodynamics course and how do they relate to one other? How are these entities and processes similar to or different from those in the heat transfer course students take? How do thermodynamics and heat transfer connect to one another, or not? What is different about how thermodynamics and heat transfer are taught in chemical engineering and in mechanical engineering, and why?

The challenge to the faculty trying to help students learn to work with people who define problems differently than they do would be to bring to the classroom the types of discussions about the relative positioning and value of thermodynamics that often appear in meetings of curriculum committees, department faculty, conferences, and world congresses. But this activity would also carry one key additional dimension, the responsibility to move beyond the defense of strengths to include the acknowledgement and articulation of limitations. Engineering students who are being trained to become leaders who listen will have to learn what they do not know.

One practical strategy for working toward this end is to require students to routinely classify problem sets in addition to solving them. Students would have to examine their textbooks in a new way, with the goal of understanding how chapters and sections differ from one another, yet are related. Consider the implications of asking students in a heat transfer course not only to solve conduction and convection problems but to be able to explain what makes these different from one another, what sorts of assumptions each makes, and what sorts of considerations get left out when one uses them in practical applications.

Learning to explain the definition and significance of the mathematical tools they gain in engineering science courses is a crucial step for engineering students to become critical analysts of their own knowledge. Furthermore, rather than diminishing the significance of that knowledge, the acquisition of such critical capabilities is arguably more likely to deepen engineers' commitments to it by enabling them to better articulate and understand what they know in relation to what co-workers know.

A more ambitious strategy would be to develop a separate course experience that is focused entirely on the question of problem definition in engineering. Such a course would focus on making visible and analysing examples of disagreement and conflict among the technical perspectives of engineers and non-engineers. Building such a course would require significant effort preparing case examples, but students who will later find themselves in senior design courses, which tend to focus on object or product outcomes, could benefit greatly from a sophomore or junior 'define' course that applied methods of case analysis, e.g., those common in business schools, to provide instruction in problem definition. Such a course could also better prepare students for the increasingly common inclusion of problem definition activities in senior design.

(2) The unique burden on the traditionally peripheral locations in the engineering curriculum would be to mold their contributions to advance the practical reasoning of engineers in problem definition and solution. It is important to acknowledge that bodies of abstract knowledge originating in the social sciences, humanities, or business management typically do not exist in a form ready for easy and uncontroversial incorporation into the heart of engineering education. Faculty from liberal arts disciplines in particular can be highly inflexible, seeking even at the undergraduate level to reproduce themselves in students rather than to adapt their modes of knowledge and practical reasoning to student trajectories. A substantial community of scholar/teachers committed to 'integrated' liberal arts education for engineers has long existed in the United States and has been energized by Engineering Criteria 2000 (Ollis and Neeley, 2003). Nurturing such communities in Europe, Asia, and elsewhere is critical to the success of redefining the core of engineering education.

The key criterion for further developing such efforts in order to facilitate their movement toward the center of engineering curricula is, once again, whether or not their contributions help students learn to work with people who define problems differently than they do. In the case of technical communication, for example, a key contribution is to help students recognize, understand, and act on the presence of 'audiences' for their work (e.g., Winsor, 1996). Engineering science training has no image of audience. Engineering ethics training calls attention to multiple roles, schemes, or mental models through such concepts as 'moral imagination', which involves learning to critically assess one's own point of view and evaluate alternative courses of action (e.g., Gorman *et al.*, 2000). All contributions to engineering education from currently peripheral positions will have to recognize that overcoming skepticism from those committed to technical problem solving will minimally require being clear, appropriately rigorous in argument and evidence, and focused on practical reasoning (see Downey and Lucena, 2005 for a description of the Engineering Cultures course).

(3) A third level of adaptation lies at the level of the curriculum. One crucial way to better prepare engineers to work amidst differences among co-workers is to acknowledge, accommodate, and even promote differences among themselves. As Figure 1 suggests, engineering curricula tend to conceptualize students in each field as one thing by picturing them as acquiring the same core or essence. Students supplement this core with technical electives and broadening experiences but most schools of engineering can and do claim that all graduates from a particular field have a specific configuration of core knowledge and, hence, core identity.

But must a degreed engineer be just one thing? After graduation, students set out on pathways that turn them into many different things, but the focus on a single essence remains. It grounds, for example, the common but highly questionable idea that once engineers become managers they are no longer engineers. Enacting a model of engineering as Problem Definition and Solution would shift the emphasis away from the person and onto the practice, i.e., away from what one has to learn to be an engineer and onto what one has to learn to do quality engineering.

Extending the core image of engineering to include the human-laden work of problem definition would free the curriculum from its felt responsibility to produce a single type of technical professional. Working as an engineer would mean both that one brings engineering technical knowledge to bear in problem solving and that one has appropriate and sufficient non-technical knowledge to map engineering and other technical perspectives in relation to one another. Much research and experimentation would be required to sort out which configurations of knowledge best prepare students to work with people who define problems differently than they do. It is reasonable to expect that, since the knowledge involved is about human beings, more than one type of knowledge and, hence, more than one type of professional identity, will be helpful.

One way to facilitate this shift is to reposition current curricula as tracks inside degree programmes that also include other, new tracks. Such a strategy would have to vary not only by country and field but also by school. For example, a current curriculum that places highest emphasis on engineering science training could become an engineering science track, structured to prepare students for research positions or graduate school. An engineering design track could include coursework in industrial design, architecture, or other design disciplines, preparing students for careers emphasizing design work. An engineering and management track would specifically help students prepare for the work of problem definition in private industry, especially by training them to analyze the types of knowledge other non-engineering managers possess and use. An engineering and policy track or engineering and society track would prepare students for problem definition work beyond the firm, e.g., in government or non-profit sectors. Extrapolating the idea, a multi-field general engineering track, degree, or possibly advanced degree programme could introduce students sufficiently to a range of fields to enable them to function effectively as mediators among different types of engineering specialists.

One benefit from developing alternative pathways to an engineering degree is that faculty would have to compete more for students, thus encouraging them to share both their knowledge and their passions in the classroom. Also, because every track would be part of a larger set, each would clearly have both strengths and limitations. What a given track lacked in depth or breadth in a particular area could be supplemented through continuing education depending upon the student's career trajectory. Importantly, the introduction of diversity to curricular structures is made theoretically possible by the shift in accreditation policies from credits to capabilities. If review teams were trained to expect diversity, engineering departments could likely develop and defend alternative ways in which their programmes meet outcomes criteria.

In general, strategies at any level to integrate problem definition into engineering education would count as formal moves to claim technical mediation as a part of the jurisdiction of engineering work, making visible and legitimizing the human dimensions of engineering work alongside technical problem solving. Such moves could not only help engineering as a profession respond to a threatened loss of control over technology, but also enable engineering education to better prepare students for what has always counted as quality work by the best engineers.

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