Chapter 21
PDS: Engineering as Problem Definition and Solution

Gary Lee Downey

Abstract All of us who teach engineers share at least one common problem: the continuing dominance of an image of engineering formation that places highest value on mathematical problem solving in the engineering sciences. The image grounds a claim of jurisdiction over technology through design. This essay offers an alternative image of engineering as problem definition and solution (PDS) and takes initial steps toward facilitating its travel. The analysis outlines four contemporary challenges to the engineering claim of jurisdiction: changes in the work of scientists, mass production of engineers for technical support, credentialing by exam alone, and shared jurisdiction through teamwork. It then explains that PDS avoids incorporating the image of "breadth" because it lacks an organized vision. Four sets of PDS practices include early involvement in problem definition, collaboration with those who define problems differently, assessing alternative implications for stakeholders, and leadership through technical mediation. Three sets of strategies for enabling the PDS image to travel include adapting pedagogies in engineering science courses, adapting pedagogies in peripheral courses, and adapting curricula to produce more than one thing. What might engineers be if a PDS image gained acceptance across the terrains of engineering formation? Could integrating PDS practices into your teaching work for you?

Keywords Engineering education • Engineering sciences • Engineering problem solving • Problem definition • Dominant images

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Introduction

Do you teach engineers? Are you perhaps an instructor in the heart of the engineering sciences, taking care to make sure your students know how to recognize and solve the difficult technical problems they will encounter on the job? Or perhaps your thing is engineering design, helping students learn how to draw on the engineering sciences to develop new technologies. Either way, might it trouble or frustrate you that prestigious reports, changing accreditation regulations, outside critics, and, perhaps, globalizing employers seem to advocate cramming all sorts of new content into engineering curricula to address their concerns? Are you feeling crowded and overwhelmed with impossible demands?

Are you perhaps an activist engineering educator, testing out new curricular strategies to help engineering students develop a broader range of skills? Do you find your opportunities limited primarily to the first and last years of degree programs? Are you feeling supplemental?

Are you perhaps an instructor in the humanities or social sciences, like me, dedicated to helping engineers become better critical thinkers and practitioners? Does it trouble or frustrate you that centers of power in the making of engineers seem to keep it focused primarily on technical capabilities? Does the force of resistance to incorporating new questions and commitments into engineering formation (Downey 2014) and engineering work still seem overwhelming despite quality critical analysis? Are you feeling left out?

All of us who teach engineers, along with others who care about or are affected by the outcomes of engineering education, share at least one common problem. It is the continuing dominance across many countries of an image of engineering formation that places highest value on mathematical problem solving in the engineering sciences. That image pictures students acquiring diverse practices of mathematical problem solving in order to apply them in the design and construction of new technologies. It links problem-solving to technological development through design. This image of engineering problem solving not only dominates the making of engineers. It has also long grounded claims by engineers to have jurisdiction over technology. By jurisdiction I mean, following Andrew Abbott, intellectual and social control over an arena of expert practice (Abbott 1988, p. 20).

The problem for those who teach in the engineering sciences or engineering design is that this image is woefully incomplete. Since at least the early 2000s, limitations in the engineering claim to jurisdiction over technology have become too obvious to ignore. It is no longer exclusive. The dominant image of engineering problem solving and technological design is scaling down.[1]

The problem for those seeking to expand engineers' skills is that it asserts a distinction between the technical and nontechnical dimensions of engineering work. That distinction makes it difficult for their work to achieve both force and coherence.

[1] For theoretical elaboration of dominant images and scale, see Downey (2009).

The problem for those who critique and resist the dominant image, claiming it is flawed, is that we have not been able to move our practices from the periphery of engineering curricula. We have not been able to successfully challenge the dominant image by offering an alternative that can scale up among engineers, let alone gain dominance. How does one overcome marginality in the face of what feels like immoveable resistance?

This essay offers the image of engineering as problem definition and solution as an alternative to the dominant image of engineering problem solving and technological design. I call it PDS for short. My purpose is to use it to enable practices of critical self-reflection to travel within and alongside practices of mathematical problem solving. The PDS image seeks to hire in, i.e., to participate critically in and inflect the dominant image rather than attempt to undermine and replace it entirely. It accepts the twin risks of co-optation and social engineering (Downey and Lucena 1997, p. 120).

The argument below elaborates the PDS image and outlines a set of practices for facilitating its travel across arenas of engineering formation. To advocates of engineering sciences and design, it claims, only partly tongue-in-cheek, that current curricula teach but half of what engineers need to know to be effective practitioners and leaders. "Collaborative problem definition" is my label for the other half. To activists in engineering education, PDS offers an alternative to "breadth" as an organizing image for new competencies. To those of us who critique engineering's continuing core emphasis on mathematical problem solving and its extrapolation into design, the argument is that PDS can provide an organizing image for integrating practices of critical self-analysis into the making of engineers. It argues that skills and speaking can function more effectively with questions and listening.

I have no illusion or expectation that integrating practices of collaborative problem definition into engineering education would be sufficient to produce technical practitioners who routinely question and thoughtfully adapt their normative commitments as everyday practices of expertise. I am suggesting, however, that such may be a necessary step, achievable by integrating the questions "What is engineering for?" and "What are engineers for?" into engineering practice at every moment. Getting there would radically reframe the next steps.

I begin by outlining four contemporary challenges to the engineering claim of jurisdiction over technological innovation. Other fields have begun claiming jurisdiction in practices of technological development. To the extent engineers acknowledge such claims, continuing to place primary emphasis on solving technical problems amounts to accepting a significant reduction in the status and value of engineering work. How can engineers claim to be unique when others do technology too?

Seeing through the PDS lens depends upon avoiding or abandoning the desire for breadth in formal engineering education. The next section argues that what that image hides far outweighs what it makes visible. The balance of the essay elaborates the PDS image by identifying four sets of constitutive practices and three sets of strategies for enabling it to travel. As analysis, it invites you to reflect on the question – "Could engineers be for more things if an image of engineering as problem definition and solution successfully gained substantial acceptance across schools of engineering?" As an attempt at critical participation, it asks if integrating PDS practices into your teaching might work for you.

The Lost Claim of Jurisdiction

Let's now examine four threats to the claim that engineers have exclusive jurisdiction over the creation or design of new technologies.

Scientists and Technology

The first and seemingly most threatening set of challenges to the engineering claim of jurisdiction over technology has come from significant changes in the work of scientists. The dominant image of engineering problem solving and technological design has long depended upon an image of science and scientists as upstream and, hence, out of the way.

The U.S. National Academy of Engineering's 2004 report *The Engineer of 2020: Visions of Engineering in the New Century* began, for example, with the simple, definitive jurisdictional claim: "Technology is the outcome of engineering" (2004, p. 7). It went on to explain that science lay upstream in the realm of unrestricted inquiry and discovery. "It is rare," asserted the report, "that science translates directly to technology, just as it is not true that engineering is just applied science. Historically, 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).

The image of science upstream had some plausibility through the mid-twentieth century. As economic historians David Mowery and Nathan Rosenberg found in analyzing time delays between discovery and application from the late nineteenth and to the mid-twentieth century, "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, p. 25). They further found, however, that by the 1980s, "scientific research was [now] loosely tied to [technological] innovation" (p. 28).

Much evidence exists of a turn toward technology among scientists, especially after the Cold War. Consider the expansion in the numbers and character of patents awarded to universities, the traditional centers for basic, unrestricted research. The U.S. National Science Board reported as early as 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 3,200 patents in 2001" (2004, pp. 5-53–5-54). The number of academic institutions receiving patents nearly tripled and the share of patents granted to them increased from 1.5–4 %. Critically, this growth centered not in engineering but "occurred primarily in the life sciences and biotechnology" (p. 5-55) The disciplines experiencing the fastest growth were chemistry, molecular biology, and microbiology.

Another indicator lay in changes in the scope of funding for scientific research. In the early 1980s the U.S. 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 2005). Also, in 1987 NSF introduced funding for multi-institutional, multidisciplinary "Science and Technology Centers" with the 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).

Beginning in the 1990s, NSF dramatically increased the number of programs linked directly to technological outputs, expanded programs that encouraged direct collaborations with industry, and rewrote virtually all science program descriptions to include technological development as a desirable outcome alongside contributions to knowledge, education, and training. It also began requiring all project summaries to demonstrate not only the "intellectual merits" of the project but also its "broader impacts" (National Science Foundation 2012). One clear way to demonstrate broader impacts is to posit links between research and potential new technologies.

The delay Mowery and Rosenberg found lay in a research world in which physics provided the dominant image of scientific knowledge production. Images blurring the claimed boundary between science and technology began to scale up with the shift toward the life sciences and information technology. In the much-celebrated field of tissue engineering, for example, the interdisciplinary collaborations of practitioners from biophysics, developmental biology, materials science, biochemistry, genomics, and several braches of medicine with chemical and mechanical engineers demonstrate the increasing comfort scientists have in associating themselves with fields that might be labeled "engineering" (Hogle 2003; Williams 2002) The same can be said for the more recent emergence of synthetic biology – the engineering of biology (Schyfter et al. 2013). Note also that many cutting-edge nanoscientists judge themselves as having fully established their professional reputations only after founding successful start-up companies (Baird and Shew 2004).

The increased degree of comfort among scientists with technological development can be found in the U.S. National Research Council's 2003 report *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 was 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 was justified, the report held, by "strong couplings" between chemists and chemical engineers in universities and industries (2003, p. 2). In short, invention and technological development no longer distinguished chemical engineering from chemistry, and it was not the label "engineering" that was being celebrated and extended.

Mass-Produced Engineers for Technical Support

A second challenge to the engineering claim of jurisdiction over technological innovation emerged from 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 judged itself to have a capacity of 4,000 students, its enrollments typically exceeded 15,000 students in any given semester. Staff members necessarily structured classwork around large lectures and annual exams, testing students' knowledge of relevant engineering sciences (confidential interview, June 2004). The implications go far beyond Egypt since that country has long been a major producer and exporter of engineering graduates trained almost entirely in the engineering sciences to countries across the Middle East.

At the 2004 annual meeting of the U.S. National Academy of Engineering, President William Wulf claimed that "new U.S. engineers account for only about 7.5 % of the world total" (Wulf 2004). He was drawing data from the *2020* study, which highlighted the "rapidly improving educational capabilities in countries like China and India" and asserted that China along was producing "more than three times the graduates in all fields of engineering than is the United States" (2004, p. 33). As Gereffi et al. (Bracey 2006; Gereffi et al. 2008) have shown, what gets reported as engineers in other countries would often be classified as technicians in the United States, with vocational certificates or associates degrees. Yet whether these are engineers or engineer-technicians, the increasing numbers in China, India, Egypt, Philippines, and other countries suggest they are scaling up an image that may well fit what engineers across the planet are perhaps increasingly becoming – technical functionaries in support positions.

The *2020* report identified two key features of this emergent image. These workers are "highly skilled… with engineering and science backgrounds," and they were "willing and able to work for wages well below those in the developed nations" (2004, p. 33). In 2005, I placed four telephone calls for technical support for a Palm Pilot. Two were answered in India, two in the Philippines. All four technicians claimed to hold bachelor's degrees in computer engineering.

One can argue that producing engineers for technical support is an American export, an industrial system that seeks low-wage workers to fuel low-cost production for mass consumption. At the same time, a key implication just may be a reverse flow of influence in what can be claimed as the jurisdiction of engineering – the scaling up of an image in which engineers are valued more for their work as technical problem solvers and less as technology creators.

Credentialing by Exam Alone

The historian of technology Rosalind Williams points toward a third, related challenge to the identities of engineers in an insightful and engaging account of institutional transformation at MIT during the late 1990s and early 2000s. Williams found that "[a]ll engineering departments are becoming, in some form or other, to a greater or lesser extent, departments of applied-information technology" (2002, p. 46). Increasing reliance on a common digital language, she argued, "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 was pulling at least some engineers into a densely populated world of information technology workers, millions of whom had already gained "engineering" credentials by passing exams rather than completing curricula.

In the 2000 U.S. Department of Education report *A Parallel Postsecondary Universe: The Certification System in Information Technology*, longtime education researcher Clifford Adelman mapped 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 (Adelman 2000). 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) labor market changes" (p. 30). These new adaptive, flexible workers realized that "work life mobility demands the transparent and portable evidence of a certification" (p. 3). This challenge may not have affected most engineers. But the easy use of the term "engineer" in such contexts illustrates the potential risk of devaluation associated with defining engineering work as technical problem solving for clients.

Shared Jurisdiction Through Teamwork

Finally, a fourth source of challenge emerged from a phenomenon that is to this day frequently characterized as a site of promise and opportunity for engineers (which it could be) – the institutionalization of teamwork in industry. Through a succession of movements including total quality management, business process re-engineering, knowledge management, and a variety of other practices, industrial organizations have worked to restructure themselves into flexible mazes of product and process development teams.

Teamwork puts engineers at the table with business managers, marketing and sales-people, researchers, labor representatives, information technology specialists, etc. Effective teamwork necessarily affords all participants some measure of responsibility over and, hence, identification with technological developments. Placing greater emphasis on teamwork in formal engineering education makes it increasingly difficult for engineers to claim jurisdiction over technology for themselves.

Indeed, to the extent engineers may be the participants most inclined to understand the problem at stake in exclusively technical terms, they might very well be least likely to respond to such shared responsibilities in other than defensive terms.

Might becoming a good team member occur in spite of core engineering training rather than because of it?

Overall, changes in the work of scientists, the mass production of narrowly-trained engineers, the rise in engineering certifications through exams, and an increased emphasis on teamwork combine to make visible a unique vulnerability in engineers' identification with technological development and dominant understanding of themselves as technical problem solvers. By claiming jurisdiction over the solving of technological problems, engineering has positioned itself as society's technological consultant, there to help but only when asked. The claim to creativity in technological development is now contested directly by both research scientists and teammates in industry. The re-visioning of engineering into technical support may be modeled by the mass production of engineers in poorer countries and easy appropriation of the label by those who certify engineers with a single exam.

Is it not now obvious to all what has long been clear to scholars in technology studies – that engineering does not (and likely never did) have jurisdiction over technological development? Many fields of engineering have been attempting to integrate bio-, info-, and nanotechnologies, in particular, into their jurisdictions by redefining the engineering sciences at their core. The replacement of unit operations in chemical engineering with multi-scale analysis is a good example (Gillett 2001). But might such efforts misdiagnose and fail to respond adequately to a more fundamental challenge? Might the main challenge facing the making of engineers in the present be to re-imagine and re-define in its entirety the obligatory core and essential heart of engineering identities?

The Limitations of "Breadth"

A key prerequisite to re-theorizing the core of engineering learning and work is to move beyond a geometry of "narrowness" and "breadth." For one thing, 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, p. 118).

But the main problem with the critique of narrowness is that it necessarily posits breadth as the solution. As Williams explained, the 1949 Lewis Report at MIT, authored by Warren K. Lewis, a founder of chemical engineering and her grandfather, labeled its central recommendation "A Broader Educational Mission." It asserted that "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, p. 67). Likewise, the *2020* report called 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, p. 5). Between these two reports, and since, are hundreds of other examples.

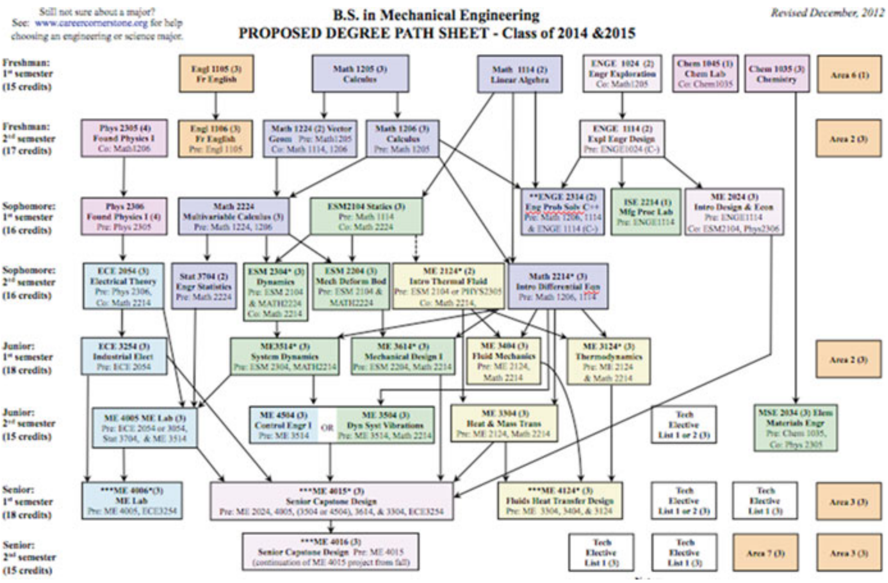

Fig. 21.1 M.E. degree path sheet

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

The image of breadth is problematic, however, 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 21.1 offers a current example of how this works. The diagram is a flowchart of a U.S. mechanical engineering curriculum distributed to students to guide them in course selection. Similar diagrams could be constructed of other curricula.

Readers need not examine the course titles and numbers inside the boxes. The diagram's key feature is the array of vertical and horizontal lines that constitute the curricular core 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. They are peripheral.

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. In this geometry, students achieve breadth through mixes of classes they select at will and integrate, or not, on their own according to their preferences and sensibilities.

The image of breadth thus lacks an organized vision. Discussions about how to overcome narrowness through breadth tend to devolve into arguments over the appropriate distribution of credits between the required core and elected peripheries. For engineering faculty who identify (or contextualize) themselves through the technical core, using it to define their identities and passions, 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 U.S. Accreditation Board for Engineering and Technology (ABET) in 2000 shifted the locus of integration among the technical and nontechnical dimensions of engineering education from credits on the student's transcript to the students themselves. These became specifications of learning outcomes, greatly energizing activists in the U.S. engineering education community. What started in the 1990s as significantly increased attention to design and information technology now included (at least in principle!) curricular interests in professional ethics, oral and written communication, teamwork, international experiences, continuing education, and more, 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 enterprises such as this one will depend upon leaving behind the critique of narrowness and its call for breadth. One reason is that technical education in every engineering field has long been itself both broad and multidisciplinary. A commitment to technical breadth is the reason why each engineering field defines itself not as a discipline but as a collection of disciplines.

A second reason for moving beyond a geometry of narrowness and breadth is that the dominant image of mathematical problem solving limits itself not by being narrow but by being incomplete. It is insufficient as a label or description. Engineering problems do not solve themselves. They are always solved by people. As soon as one introduces people into problem solving, the human dimensions of the process become obvious. When it imagines mathematical problem solving as technical work alone, formal engineering education abstracts out what it counts as human dimensions and defines these as extraneous and irrelevant. It can do so no longer. The long-claimed jurisdictional space for engineering has eroded.

Those of us who teach engineers need a dominant image that both encourages and guides competition over the panoply of potential changes facing engineering curricula and engineering work. The *2020* report pointed in this direction when it observed, "In many ways the roles that engineers take on have always extended beyond the realm of science and technology" (2004, p. 37).

PDS: Adding Problem Definition

One way of formally recognizing the core human dimensions of engineering work is to acknowledge that engineering problem solving has always included activities of collaborative 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. They do so in ways that go far beyond laudable, but still limited, efforts to expand the umbrella of technical "specifications" and "needs assessment" in engineering design. One potentially promising way of remapping the jurisdiction of engineering work to adapt effectively to the challenges of the present may be to redefine it in terms of both problem solving and problem definition.

An image of engineering as Problem Definition and Solution, or PDS, would have at least four key sets of practices. To illustrate these, consider an extrapolation from a well-argued proposal by Geoff Moggridge and Ed Cussler (2000) 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 (a) identifying needs, (b) generating ideas, (c) rationally selecting among available ideas, and (d) identifying how to put solutions into operation, including building and testing prototypes and estimating costs. The proposed procedure is attractive because it explicitly pushes chemical engineers beyond the purely technical decisions that are typical in conventional models of process design, e.g., batch vs. 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 been 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.

Early Involvement in Problem Definition

The first set of practices in a PDS image 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 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 image would focus the engineers' attention much earlier, before the problem has been negotiated, described, and, in perhaps a minority of cases, 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 the work of 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, etc. 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 integrate problem definition into mathematical problem solving would involve themselves early in processes of problem solving, prior to the point at which a clear design problem emerges or can be claimed. These engineers would participate by bringing to bear valuable technical knowledge about chemical process development, 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.

Collaboration with Those Who Define Problems Differently

A second set of practices in the PDS image 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 analyzed in mathematical terms. 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 quantitative 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, analyzing 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, affected workers, and local residents. 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 move in collaborative PDS work involves investigating and assessing other perspectives. Its success depends upon the prior knowledge and conviction that one occupies only one point of view among many in negotiations of technological developments. Also, 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. They would also strive to understand these technical issues from different points of view and critically recognize and examine the limitations of their own perspectives.

Assessing Alternative Implications for Stakeholders

The third set of practices in the PDS image involves assessing the implications of alternative solutions for stakeholders. Such work, which has both technical and nontechnical dimensions, 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. It is still toxic, however. Engineers who defined their work as problem definition and solution would include in their jurisdiction responsibility for analyzing from workers' points of view the implications of substituting a still-toxic solvent for 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 exception or part of a long-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 set of stakeholders.

Solving technological problems typically changes the relationships among participants in one way or another. While 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, e.g., the interests of senior managers, 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 power dimensions and would draw on their training to find ways of dealing with both at the same time.

Leadership Through Technical Mediation

The fourth set of practices in the PDS image involves exercising engineering leadership through a seemingly novel but actually quite common path – technical mediation. In conventional definitions of engineering work, engineers have to make difficult trade-offs among alternative needs or design specifications. In the PDS image, engineers may 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. Mediating among the positions of stakeholders, whether between employer and regulatory agency, between employer and others affected by the employer's work, between workers and management, among workers, among managers, etc., engineers would continue seeking solutions to meet technical needs but also add the work of reconciling differences in defining them.

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. In the cheque-printing case, the new product design engineers discard the idea of changing the presses because "the company does not want to make the enormous capital investment involved" (p. 10). Also, if electronic data processing replaced hand-written cheques, "the company may decide that… printing cheques is like making buggy whips" (p. 10). PDS engineers would certainly have to understand and fulfill 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 drawn from and attributed to others elsewhere.

Technical mediation is neither absolute subordination nor resistance to management. Nor is it a search for often unattainable consensus judgments. Rather the process takes into account the fact that final decisions affect the next round of decision-making, for technical deliberations necessarily begin with the outcomes of previous deliberations. Reconciling definitional differences as much as possible maximizes the possibility that the process is easier next time around.

Some engineers have told me that labeling engineering work "mediation" would appear to demote it. But the purpose is to avoid the explicit demotion to technical support, as outlined above. Quality engineering work already involves mediation even when it privileges creative technical genius. Engineers already see genius in design as requiring difficult but clever trade-offs among alternative needs or specifications. The PDS image makes visible the fact that creative engineers also make difficult trade-offs among alternative stakeholders, alternative definitions of the problem, and alternative perspectives about what is taking place. Technical mediation can be creative work indeed.

When advocates of engineering position it as waiting for society to ask it for help or give it problems to solve (including via the narrower interests of employers), they fail to fulfill a responsibility to bring its technical knowledge to bear in the definition of problems in the first place. They also deprive others of the opportunity to look to engineers for leadership in problem definition. The *2020* report romantically pictured engineering "strengthen[ing] its leadership role in society" and envisioned engineers working "as leaders who serve in industry, government, education, and nonprofit organizations" (2004, p. 48). Perhaps it is even more romantic to picture engineering identities and responsibilities extending beyond the interests of employers. David Noble (1977) certainly made that case while characterizing engineers as lackeys for capitalism. But I maintain that engineers in fact routinely imagine problem definitions and service outcomes that extend well beyond the boundaries of the firm, even if also commonly through it and not always consciously.

The point here is that visible leadership for engineers will likely not come through claims of technical genius and technological heroism when engineers do not have jurisdiction over technology in the first place. Visible leadership qua engineers may never come. But might the hard work of including collaborative problem definition in engineering work as a core competence, responsibility, and set of practices offer a more realistic pathway than hanging onto a declining image?

Integrating Problem Definition into Engineering Education

A 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, effective travel toward some new desired state of being must always start "here," in the present and at this location. Engineering curricula virtually everywhere tend to include a technical core and non-technical periphery. The most difficult challenge in the work of integrating problem definition into engineering education is to locate and champion both technical and non-technical knowledge practices at the core – education in the engineering sciences. The efforts required include, minimally, 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 knowledge practices in ways that engage the practices of mathematical problem solving while also promising to help engineers understand and critically engage diverse technical perspectives on the job; and (3) adapting engineering curricula in ways that legitimize and encourage students to become more than one thing.

Adapting Pedagogies in Engineering Science Courses

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 his 1994 book *Designing Engineers*, MIT engineer Louis Bucciarelli offered a helpful tool for addressing this issue with the image of "object worlds." Bucciarelli's point was that each engineering science creates and lives in one or more object worlds into which engineers must enter 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 wrote, "design is the intersection of object worlds" (1994, p. 20). Systematically examining three design projects that experienced high levels of uncertainty, Bucciarelli found 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 observed how engineers and other professionals working in 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 educators 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 posits a unique configuration of theoretical entities and processes. Engineering science faculty who devote 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? 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 bring to classrooms the types of discussions about the relative positioning and value of thermodynamics that often appear in meetings of department faculty, curriculum committees, conferences, and world congresses. But such activities would also carry one key additional dimension, the responsibility to move beyond the defense of strengths to include acknowledging and articulating 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 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 focused specifically on the issue of problem definition in engineering. Such a course would make visible and analyze examples of disagreement and conflict among the technical perspectives of engineers and non-engineers. Building such a course would require significant effort preparing case studies. Yet students who will later find themselves in senior design courses, which tend to focus on object or product outcomes, could benefit greatly from a second- or third-year "define" course that applied methods of case analysis to instruction in problem definition. Such a course could also better prepare students for the increasingly common inclusion of problem definition activities in senior design.

Adapting Pedagogies in Peripheral Courses

The unique burden on the traditionally peripheral courses would be to mold their critical contributions to advance the knowledge practices of engineers in collaborative 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 formal engineering education. Faculty from liberal arts disciplines can be inflexible themselves, especially when they seek to reproduce themselves in students rather than to adapt modes of knowledge and practical reasoning to student trajectories.

Substantial communities of scholar/teachers committed to "integrated" liberal arts education for engineers were heartened by Engineering Criteria 2000 in the United States (Ollis et al. 2004) and their analogs in other countries. Once again, a key criterion for facilitating their movement toward the center of engineering curricula is 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, an important contribution is to help students recognize, understand, and act on the presence of "audiences" for their work (Winsor 1996). 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 (Gorman et al. 2000). Those of us who seek to move our practices from peripheral positions toward the center may have to formulate and focus our critical analyses in ways that maximize the possibility of informed and effective critical participation.[2]

[2] The PDS image evolved from pedagogical strategies in my Engineering Cultures course, an elective that seeks critical participation from the periphery (Downey 2008, 2009, 2011b).

Adapting Curricula to Produce More than One Thing

A third type of adaptation lies at the level of the curriculum. One crucial way to better prepare engineers to work amid differences among co-workers is to acknowledge, accommodate, and even promote differences among themselves. Engineering curricula tend to picture students as acquiring the same core or essence. Although students supplement this core with technical and nontechnical electives, most schools of engineering claim that all graduates from a particular field have a specific configuration of core knowledge and expertise, and, hence, core identity.

Must a degreed engineer be just one thing? After graduation, students set out on pathways that turn them into many different things, yet the focus on a single essence remains. It grounds, for example, the common but highly questionable claim that once engineers become managers they are no longer engineers. Scaling up a PDS image would shift the emphasis away from the minimum requirements to become an engineer and toward the diversity of practices that constitute quality engineering. Working as an engineer would mean that one brings to the field arrays of practices in both mathematical problem-solving and the mapping of perspectives and personnel in relation to one another.

Much research and experimentation would be required to sort out which configurations of knowledge and expertise better prepare students to work with people who define problems differently than they do. Yet it is reasonable to expect that more than one type of knowledge practice and, hence, more than one type of practitioner identity would be essential.

One way to facilitate this shift is to reposition current curricula as tracks inside degree programs that also include other, new tracks.[3] 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 program 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 knowledge and passions in the classroom. Also, because every track

[3] A version of this proposal to develop tracks in engineering departments also appeared in Downey (2011a).

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 programs 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 part of the jurisdiction of engineering work. Such moves could not only help engineers recognize they do not have jurisdiction over technology, but also enable practices of engineering formation to better prepare students for what has always counted as quality work by the best engineers.

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