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Introduction

The National Academy of Engineering (NAE) released its report *Grand Challenges for Engineering* in 2008, describing 14 major engineering challenges that must be overcome to make the world "a more sustainable, safe, healthy, and joyous—in other words, better—place."[1] The challenges identified encompass areas as diverse as energy, environment, infrastructure, health, security, learning, and research, but in each case the emphasis is on "engineering" dimensions of the larger problem domain and, in particular, on the technologies and tools that might enable solutions to evident, often enduring challenges facing contemporary civilization.

Since its publication, the report has drawn significant attention from the engineering community and has been the subject of two national summits, Obama Administration initiatives, and STEM education programs, both K-12 and university.[2] Industry leaders also have been eager to demonstrate the connection between their activities and the grand challenges, such as IBM's Big Green Initiative, which claims to address a number of challenges identified in the NAE report.[3] Given this attention, and the general enthusiasm with which it has been received, the NAE *Grand Challenges for Engineering* report (hereafter *Grand Challenges*) offers an intriguing opportunity to reflect on how engineers imagine what engineering is and what its proper role in society ought to be.

This paper contributes one such reflection, carefully analyzing *Grand Challenges* as a way to interrogate broader social and cultural meanings surrounding engineering, technology, and their relationships to major social and environmental problems. While sympathetic to the impulse underlying the report, namely to direct engineering energies toward "the century's great challenges,"[4] our analysis identifies key assumptions embedded in *Grand Challenges* that are likely to constrain efforts to develop robust solutions. This paper argues that, in important respects, *Grand Challenges* relies on a problematic and increasingly outdated understanding of engineering as distinct and apart from the social contexts in which it is practiced—in other words as "purely technical" at its foundation. As we will show, this understanding works in tension with the desire to shift engineering (as a whole) toward social problem solving by misconstruing critical attributes of both the social problems being addressed and the technologies intended to solve them.

In terms of engineering solutions to social problems, the most obvious and problematic aspect of *Grand Challenges* is its facile distinction between technical and social aspects of engineering, situating the technical dimensions as "opportunities" to be embraced and the social dimensions as "barriers" to be overcome. Surely, the flip side of every problem is an opportunity for improvement, but the language of technical opportunities and social barriers exposes critical assumptions held by the authors about how social problem solving is best to proceed. One such assumption involves the responsibilities of diverse partners in responding to the grand challenges; reductively put: engineers (and scientists) are to lead and politicians, policy makers, and the public are to provide resources (primarily funding) and trust (by getting out of the way). Although this model may be sensible from the perspective of narrowly technical decision making, we argue this is a troubling way to think about engineering if it is to systematically and effectively contribute solutions to grand-challenge-type problems.

In identifying and describing problematic approaches taken in *Grand Challenges*, our purpose is not merely to offer a detached, academic critique. Instead, we are motivated by a desire to reframe "engineering" in ways that make it more amenable to social problem solving and to help engineering decision makers more productively engage the various, mostly social, forces influencing their work. Hence, after working through some of the most problematic assumptions and approaches evident in *Grand Challenges*, we then propose alternative understandings of engineering that are more in line with the complexities of the grand-challenge problems. These alternative understandings synthesize insights being developed within the engineering studies community (and within science and technology studies more broadly) over the past few decades. In our assessment, the alternative understandings promise more imaginative engineering approaches and more robust contributions to enduring social problems. We proceed with our analysis by extending these alternative understandings of engineering into the educational context, arguing for curricula that better integrate the technical and social dimensions of engineering problem solving.

Methods and Scope

The paper's analysis is based primarily on a close reading of *Grand Challenges*, focusing attention on the report's underlying assumptions and their implications for social problem solving. As indicated above, we take the report as representative of how engineering and its relationships to various social contexts are dominantly understood, both inside and outside the engineering community. *Grand Challenges* provides the primary empirical material of our analysis, but we also draw comparisons between *Grand Challenges* and two prior NAE reports, *The Engineer of 2020*[5] and *Educating the Engineer of 2020.*[6] After carefully reading and coding the texts of *Grand Challenges*, we identified recurring themes with respect to "technical" and "social" (political, organizational, cultural, etc.) facets of engineering as a domain of problem solving and as a situated practice. These themes were then categorized and ordered into the main points described in the next section. After carefully analyzing and questioning these themes, we referred to *The Engineer of 2020* and *Educating the Engineer of 2020* for insights to clarify and highlight how alternative assumptions might offer a more promising vision for reorienting engineering to grand-challenge problem solving. We then extended these alternative understandings into the educational context by connecting to engineering education initiatives aimed at bridging the social and technical domains, especially through the teaching of design.

The *Grand Challenges* text is significant and deserving of systematic attention for two reasons. First, it resonates strongly with participants in engineering and engineering policy making and education as evidenced by its uptake, dissemination, and frequent referencing. The approach taken in *Grand Challenges* clearly aligns with the perspective taken by a wide—and probably influential—audience interested in engineering, education, and their reform. Second, the report's authors disproportionately represent corporate and research institutions (numbering 15, with 3 exceptions—one journalist, one politician, and one development banker), suggesting that it provides mostly an "internalist" account of engineering and its relationship to social problems. As an internalist account, the perspective provided is from that of (particularly situated) practicing engineers and emphasis is placed on those variables within those persons' primary domain of influence. Given this perspective, it is not surprising to see a more-or-less neat demarcation between technical opportunities and social barriers, which makes it even more important to challenge this taken-for-granted demarcation. Hence, while the scope of our empirical material is narrow, the implications of our analysis are broad.

"Engineering" as Represented in *Grand Challenges*: The Technical-Social Divide

The *Grand Challenges* report puts forward an image of engineering that is gallant, perhaps even heroic. The report opens: "Throughout human history, engineering has driven the advance of civilization."[7] It later adds that engineering brings together "the rules of reason, the findings of science, the aesthetics of art, and the spark of creative imagination" and has "revolutionized and improved virtually every aspect of human life."[8] The veracity of such generalized claims is impossible to determine, and, besides, this particular vision of engineering serves in the report mostly as a set-up for the big challenges ahead. Nevertheless, from its beginning, *Grand Challenges* frames engineering as a domain of achievement and mastery, as having tried-and-true techniques for solving big problems, and as already ready for the challenges ahead.

Perhaps not surprising in a report of this type, *Grand Challenges* also characterizes engineering in a way that may be inspiring for the uninitiated but is otherwise problematic. The boundary between engineering and other disciplinary or professional realms is inconsistently applied and strategically played across the report. *Grand Challenges* identifies humanity's great achievements as *engineering* achievements, even where the connection is tenuous (e.g., the taming of fire[9]). At the same time, it leaves totally unaddressed engineering's contributions to social and ecological problems, including those some of the central problems underlying the grand challenges.

The report states: "For all of these [engineering] advances, though, the century ahead poses challenges as formidable as any from millennia past,"[10] but then frames the problems as inevitable byproducts of civilization's progress (e.g., caused by population growth, consumer demand, etc.) rather than unintended consequences of intended human actions—including engineering problem solving. For example, as the report celebrates engineering's contribution to agriculture, it is silent about engineering's contribution to creating the synthetic fertilizers that disrupt the natural nitrogen cycle. As the report salutes the great achievement of the automobile, it is silent about automobiles' contribution to the grand challenges associated with excessive energy consumption and urban congestion. Even the grand challenges of controlling carbon emissions and preventing nuclear terror are disassociated from their engineering origins.

Similarly, *Grand Challenges* is silent about the likely unintended consequences of the technological solutions proposed for the 14 grand challenges identified. For example, the report claims that providing energy from fusion has a lot of advantages, including its inherent safety (unlike with fission, run-away reactions are not possible with fusion). Other reasonable safety concerns—like waste management and effluents[11]—are left unaddressed, as are unintended (but anticipatable) consequences more generally.

We draw attention to these silences in the report not to suggest that the solution paths identified are inappropriate, but instead to highlight the double standard applied to social and technical facets of engineering throughout the report: While (technical) engineering is cast as responsible for advancing civilization (a social phenomenon, to be sure), it is not also seen to be responsible for the ills resulting from engineered systems. While engineers should be prideful of the social benefits of the technologies they (collectively) have devised, there is no reason, according to the report, to blame engineers for the social detriments of those same technologies.

Although the report's authors claim not to have endorsed any particular approach to addressing the grand challenges identified, in fact a very particular approach to problem-solving is offered. This approach takes existing engineering problem-solving techniques as sufficient (if not inevitable); it subsumes all the good associated with technological advance under "engineering" and externalizes or ignores the bad; and it puts forward narrowly technical solution paths to the complex social problems underlying each of the grand challenges. By reducing complex social phenomena to narrow technical problems amenable to traditional engineering training, *Grand Challenges* limits engineers' responsibilities to their existing, narrow technical expertise. Simultaneously, the report externalizes responsibility for the ("social") barriers that prevent or slow the creation of engineering solutions. This approach to engineering is historically dominant to be sure, connected centrally to the mainstay argument that technology is neutral. But as with the neutrality argument, the dominance of the *Grand Challenges* approach to engineering does not mean it is inevitable or even desirable.[12]

<u>Defining Engineering as Technical Problem Solving</u>

Grand Challenges' asymmetrical treatment of technology—with the benefits of technology attributed to engineering and the liabilities to other factors—reflects a crucial assumption that carries across the report, namely, that technology challenges can be neatly separated into technical and social factors. Technical factors include various means of increasing efficiencies, refining processes, and facilitating basic scientific research. Such means, the report implies, are the best (perhaps the only) way engineers might go about addressing grand-challenge problems. Just as engineering is understood narrowly around technical factors, so too are broader social factors understood (narrowly) as external to, but impinging on, engineering: "governmental and institutional, political and economic, and personal and social barriers will repeatedly arise to impede the pursuit of solutions to problems."[13] With the sometimes exception of economic factors (particularly, costs), *Grand Challenges* articulates organizational, political, and cultural factors both as outside engineering and as "barriers" to be overcome wherever they exist in tension with achieving narrowly specified technical goals.

The technical-social division is especially problematic in how *Grand Challenges* translates complex sociotechnical challenges into narrowly technical challenges and then suggests that existing technologies or engineering developments currently on the horizon are capable of solving these technical challenges. An example of such a reductive interpretation of grand challenges is the discussion about personal learning. The report starts by drawing attention to individual differences in learning and stating that existing educational approaches lack flexibility in meeting individual needs. While this set-up hints at the importance of addressing different learning styles, personalities, motivations, and so on—in other words, looking at the full complexity of the challenge of individualized education—the report then turns abruptly toward a narrow technical sub-problem: optimizing learning outcomes by manipulating the sequence in which materials are presented to students. To achieve this radically narrowed goal, the report introduces a computer algorithm that "eliminates unsuccessful presentation sequences and modifies successful ones for a new round of tests, in which the least successful are again eliminated and the best are modified once more."[14]

As most thoughtful educators recognize, sequencing of material is a minor variable in the larger equation of successful (individualized) learning. What material is included, how materials are connected to students' existing knowledge and experiences, and the dynamic of the learning environment are all widely recognized as more significant than the ordering of content alone.[15] As with most other examples, the particular solution offered and the (radically) narrowed technical problem it "solves" are perfectly acceptable as far as they go, but they do not go far enough. Individual learning differences demand attention to a wide set of pedagogical and curricular variables, and devising solutions to this larger problem requires both an appreciation of the problem's complexity as well as an understanding that optimizing any given approach does not substitute for the arguably more important judgment about what ought to be optimized.

At a higher level of abstraction are questions surrounding the purpose and roles of education and the institutional and economic contexts in which education takes place. Without considering the "higher purposes" of education, for example, the report says nothing about how the computerized learning model proposed might facilitate critical thinking, commitment to the educational process, lifelong learning, or student ability to identify and solve problems for themselves. The report is also silent about structural problems surrounding the current American educational system in particular, such as the lack of qualified and dedicated teachers, the under-representation of minority groups in higher education, waning interest in STEM fields, etc.[16] By abstracting the proposed technical solution from the larger social context of education, *Grand Challenges* identifies one potentially relevant research agenda, certainly, but not one that addresses anywhere near the complexity of the initially stated problem.

By stripping away the social and political context of big social problems, *Grand Challenges* not only oversimplifies the nature of the challenges; it also fails to encourage engineers to assume prominent roles in collaborations initiated outside narrow technical realms. The report's approach to the challenge of providing clean water and basic sanitation in developing countries showcases such a miss. Whereas water is a scarce resource in many places in the developing world, the problems of consistent supply of clean water and sanitation services raise much broader questions than water purification or desalination systems alone can answer. Questions about infrastructure installation, health-care management, public investment, and ownership and use rights surrounding water resources are all essential components of the water and sanitation problems faced by poor communities globally.[17] To be fair, the report does recognize political and economic facets of the challenge of water provision, such as the prevalence of inequities in distributing water resources. Yet it limits the *engineering*-relevant focus to desalination, distillation, and purification technologies alone.

The solar energy challenge is another example of reducing a complex and largely uncertain problem (making solar energy systems affordable) into specific technical indexes. In this example, *Grand Challenges* implies the necessary techniques are already in hand; the need is merely to continue refining (and ramping up investment in) developments already well along. The report discusses in detail the prospect for new technologies' increased efficiency in transferring solar energy to usable forms, as if promising solutions to the solar challenge merely await technical implementation. Despite the report's emphasis on efficiency in this section, the connotation of the term "efficiency" here is vague and mercurial. The report discusses, in turn, the converting efficiency of commercial solar cells, the theoretical maximum efficiency of current standard cells, new materials and experimental cells, and the theoretical efficiency of nanocrystal-based systems. Apart from these imagined theoretical data, the report does not explain the net-gains of each solar energy project, the overall costs per unit energy generation and delivery, or the political landscape that shapes America's renewables energy policy (e.g., Obama Administration support for renewables on the affirmative side and fossil-fuel lobbyists on the negative).

As we question the sensibility and viability of limiting understandings of engineering to the narrowly technical, we do not also question the sensibility or viability of narrowly technical expertise within engineering. To the contrary, we believe traditional technical skills are both essential and essentially desirable, but only so in an understanding of engineering that spans both technical and social domains.

The Role of Non-Technical Participants in Grand-Challenge Problem Solving

The translation of complex sociotechnical challenges into narrow technical ones has implications for engineers' understanding of their relationships with other stakeholders. *Grand Challenges* extends its conceptual separation of technical and social factors to the division of labor between engineers and other practitioners. Engineers (along with scientists) are put forward as ideal role models for advancing grand-challenge solutions and others are cast as impediments, either resistant to or not adequately supporting the technical solutions offered by engineers. The role of participants outside of technoscientific disciplines, according to the approach taken in *Grand Challenges*, is merely to facilitate scientific and technical progress. The report occasionally recognizes the necessity of engineers communicating with non-engineering groups in dealing with the non-technical aspects of engineering problem solving, but that is only to facilitate or otherwise enable technical research and development. Ultimately, it is engineers who possess the requisite technical expertise and, therefore, should play the primary role in tackling the grand challenges.

Grand Challenges characterizes the role to be played by non-engineers as one of deference. The report indicates awareness that the public image of engineering is not always congruent with engineers' self-understanding, and it attributes the incongruence to public ignorance of engineering and (irrational) resistance to technological innovation. Therefore, an implicit agenda of *Grand Challenges* seems to be propagating within society at large increased trust in the capability and authority of engineering, and "an appreciation of the ways that scientists and engineers acquire the knowledge and tools required to meet society's needs."[18] As the report states in its introduction,

> The ultimate users of engineering's products are people with individual and personal concerns, and in many cases, resistance to new ways of doing things will have to be overcome. Teachers must revamp their curricula and teaching styles to benefit from electronic methods of

> personalized learning. Doctors and hospital personnel will have to alter their methods to make use of health informatics systems and implement personalized medicine. New systems for drug regulation and approval will be needed when medicines are designed for small numbers of individuals rather than patient populations as a whole.[19]

In each of these cases, the new technologies are assumed to be superior to existing approaches and to be linchpins in address the underlying (social) problem. Non-technical practitioners in each domain are cast not as collaborators in problem solving or even as resources to be drawn on by engineers, but only as potential nodes of resistance.[20]

The ideal relationship between engineers and scientists is more ambiguous in *Grand Challenges*. On one hand, as engineers frequently legitimize their expertise with the authority of scientific knowledge, or even view engineering as an "applied science,"[21] scientists are viewed as natural allies. At the beginning of the report, the authors characterize engineering as "[a]pplying the rules of reason, the findings of science, the aesthetics of art, and the spark of creative imagination."[22] Scientists are paired with engineers throughout the report: "In the century ahead, engineers will continue to be partners with scientists in the great quest for understanding many unanswered questions of nature."[23] On the other hand, *Grand Challenges* distinguishes engineers' unique contributions, even to science: "In the popular mind, scientists and engineers have distinct job descriptions. Scientists explore, experiment, and discover; engineers create, design, and build. But in truth, the distinction is blurry, and engineers participate in the scientific process of discovery in many ways."[24] Here again, the report plays the boundaries of engineering loosely, in this case the boundary between science and engineering, to cast engineering in its most favorable light.[25]

The tension in engineers' ambiguous relationship with scientists represents an opportunity for engineers to embrace more collaborative and interdisciplinary inquiry into ever-more complicated sociotechnical challenges. As engineers seek to expand their roles in what are traditionally considered arenas for scientists, architects, doctors, educators, or even policy makers, they are bound to question and redefine the scope of engineering as an enterprise, and *Grand Challenges* offers opportunities for engineering to be understood in a way that includes factors beyond the technical. For example, the report repeatedly points out that contextual matters (e.g., the state of material, political, or organizational infrastructure surrounding water and sanitation solutions or computer security protocols) are important in specifying technical solutions. The report also occasionally emphasizes that synergy across a number of interconnected fields is needed to tackle certain types of challenges (but even here the emphasis is placed on technoscientific dimensions of problems). For example, the report suggests that personalized medicine "will be addressed by the collaborative efforts of researchers from many disciplines, from geneticists to clinical specialists to engineers."[26] These openings point the way toward a more expansive understanding of engineering and its potential contributions to grand-challenge problems, but the report does not follow through with this approach, which we take up in the following section.

Alternative Framings of Engineering: Beyond the Social-Technical Divide

Contrary to the approach taken in *Grand Challenges*, we argue that effectively responding to big social problems requires rethinking engineering—both what it is understood to be and how it is practiced. This section and the next draw on two additional NAE publications, *The Engineer of*

2020 and *Educating the Engineer of 2020*, in an effort to identify approaches to engineering that do not rely so heavily on the problematic assumptions described above.

Instead of groundless confidence in the adequacy of current or emerging technologies for responding to grand challenges, we argue that acknowledging uncertainties—in both existing engineering approaches and in understandings of the problems being addressed—is an important starting point. *The Engineer of 2020* adopted such a stance: “The particular factors that will dominate engineering practice and require reform of engineering education are not predictable.”[27] According to this vision of an uncertain future, conventional problem-solving techniques may well be inadequate for tackling intricate future challenges. Additionally, some of the problems that will confront engineers in the future are likely to be unknown in the present. A more realistic alternative for mapping out the future is to admit that neither engineers nor others can be certain about the variables that will shape the future and to focus instead on developing strategies for coping with uncertainties.[28] Nowhere in *Grand Challenges* do we see a call for engineers to direct their energy towards better monitoring or on-going analysis of grand-challenge-type problems as they arise and evolve. In what is perhaps an ironic twist, the approach to engineering offered by *Grand Challenges* would be incapable even of adequately discerning the problems put forward by the report as grand challenges, given that they arise and exist beyond the boundaries of narrowly technical engineering.

In comparison to *Grand Challenges*, *The Engineer of 2020* seeks to explore new roles of engineering and engineers in a changed context. As an entry point, *The Engineer of 2020* identifies one unchanged feature of what is otherwise an ever-changing future: the interconnection between engineering and society. It states, “The future is uncertain. However, one thing is clear: engineering will not operate in a vacuum separate from society in 2020 any more than it does now.”[29] The remainder of this section explores three dimensions of this enduring feature, elaborating ways engineering knowledge and practice are entwined with “the social.” First, we consider the marginalization of the social in engineering and offer a more integrated model. Then, we look at engineering practice and how engineers might be more productive (in terms of grand-challenge problem solving) by collaborating on more diverse teams. Third, we propose a more reflective and critical stance toward engineering *by engineers* in order to promote a more realistic, more balanced appreciation for what can and cannot be achieved under the current model. In the following section, we draw out implications these alternative understandings of engineering have for engineering education.

Engineering as Sociotechnical Practice

The Engineer of 2020 takes a decidedly different stance than *Grand Challenges* on the relationship between the technical and social dimensions of engineering. Rather than considering political, organizational, and cultural concerns as external or barriers to approaching important engineering challenges, it sees these as always existing alongside technical dimensions of engineering practice.[30] According to the report, “it is not just the nature of a narrow technical challenge but the legal, market, political, etc., landscape and constraints that will characterize the way the challenge is addressed.”[31] As a result, confronting complex engineering challenges, such as updating and securing information and communication infrastructure, as suggested by the report, “will clearly involve legal, regulatory, economic, business, and social considerations."[32] It is worth noting that, according to *The Engineer of 2020*, social considerations are not merely minor variables that happen to intersect with engineering practice. Rather, "consideration of social issues is central to engineering,"[33] and, hence, engineering might more accurately be understood as "sociotechnical" practice.

The Engineer of 2020 does not suggest this integrated approach to engineering be created from whole cloth. Because engineers are comfortable with "systems analysis," the report urges them to extend the scope of the "systems" they already consider, specifically by including facets of social systems alongside the technical. To do this, engineers will have to enrich their existing expertise with better understandings of public policy and community needs as well as enhanced social and political acumen. While experts in other domains have roles to play in fleshing out our understandings of sociotechnical systems, engineers share responsibility for integrating diverse insights into a coherent model and, ultimately, for achieving synergy between technical and social dimensions of the system. Such a reorientation would probably be beneficial for many domains of engineering practice, but it is absolutely necessary if engineering is to take seriously social problems of the sort identified in *Grand Challenges*.

Better integration of the social and technical facets of engineering is one way to improve grand-challenge problem solving, but engineers might also bring themselves more fully into traditionally "non-engineering" domains. For example, engineers need not assume policy-making is external to their work, but instead might take a more active role in engineering-related policy making, analyzing the public gains and losses of their projects, collaborating with a range of stakeholders in establishing promising policy directions, and otherwise providing input to the (hopefully democratic) political process. *Grand Challenges* laments the existence of not-always-favorable political environments, implying engineers' involvement in politics and policy making is a necessary evil. *The Engineer of 2020*, on the other hand, sees politics as part and parcel of engineering. As the report suggests, "the engineers of 2020 will be actively involved in political and community arenas."[34] While not sole crusaders speaking truth to power, responsibilities for mobilizing political interests and building the political resolve needed to advance beneficial engineering projects fall on engineers as much as anyone. So too do responsibilities for the negative consequences of technological (that is, sociotechnical) innovation. Hence, engineering should be held accountable for devising precautionary measures with both technical and political dimensions.

As with politics, engineering would be better situated to address grand-challenge problems if engineers did not take as "given" the apparent public demand for particular engineering solutions. What is demanded by consumers and society—as well as what is understood to be desirable, or even viable—is contingent on a range of factors, some of which engineers could take responsibility for redirecting. *Grand Challenges* offers a glimpse at such a strategy by advocating systems "designed to be compatible with human users," but then reveals the ultimate goal of this approach is "ensuring user cooperation with new technology."[35] A more productive approach to the user-technology relationship would be to ensure new technologies cooperate with their users or, more precisely, that new technologies are perceived to be worthy of accommodation by users.

In this reframing, the onus is placed on the designers of new technologies that are inserted into people's lives, rather than the other way around. This does not mean that user-resistance should halt new initiatives, but that the initiatives need to be made more salable to their intended audience. Extending this line of reasoning, engineers might do better in addressing grand-challenge problems by questioning (existing) market demand as the final arbiter of what projects get done. Instead, engineers could take market conditions as part of their domain of influence—not only identifying market opportunities and constraints and accepting them as fixed, but leveraging alternative institutions (e.g., politics, the media, education and marketing) where market demand proves to be inadequate.

A Multiple-Stakeholders Model of Collaboration

Determining the new roles for engineers in the future relies on serious communication between engineering and non-engineering groups. Again, this is explicitly recognized by *The Engineer of 2020*, which notes "it is important to engage all segments of the population in a vigorous discussion of the roles of engineers and engineering and to establish high aspirations for engineers that reflect a shared vision of the future."[36] It is untenable to assume engineers can or should develop technological solutions to social problems independently of professional and social groups with other expertise and perspectives. Real-world problems know no disciplinary boundaries: technical, financial, political, and cultural components intertwine. While professional grandstanding may serve in a limited way to advance engineering's public image, romanticizing engineering as the "driver of civilization" probably undermines its credibility among many observers. Instead of defining themselves as apart from (and above) other professional groups, engineers would do better to articulate a future for the profession that prioritizes collaboration with players beyond research scientists—policy makers, business leaders, social scientists, end users, and others.

Our proposed model of collaboration does not entail engineers merely departing their knowledge to others—providing the technical input upon which others will draw. It requires engineers to reformulate their role in response to dynamic, sometimes unpredictable interdisciplinary problem-solving contexts. *The Engineer of 2020* recognizes that to "build a clear image of [their] new roles," engineers will have to "accommodate innovative developments from nonengineering fields."[37] That means "engineering" itself should be open to change through the process of interdisciplinary collaboration with other expert groups. This approach applies equally to engineering's relationship to the larger public, which again diverges from what is evident in *Grand Challenges*. *The Engineer of 2020* identifies "excellence in communication (with technical and public audiences)" as "essential attributes" for future engineers.[38] Effective communication skills are surely needed to better educate the public concerning engineering principles and possibilities, but good communication is always a two-way street: As it does with other expert groups, engineers should conceive of the public in a way that offers potential for learning and not only teaching (or preaching) about what engineering has to offer.[39, 40]

Engineering, Warts and All

As mentioned above, *Grand Challenges* avoids recognizing engineering's responsibility for contributing to grand-challenge-type problems, and it does so in two ways. First, the report attributes the causes of grand-challenge problems to non-technical factors, keeping silent about the roles played by technologies in creating or exacerbating the problems. Second, because the report implies engineering is responsible only for "the technical" dimensions of technology making, it immunizes engineering from accountability for the non-technical causes of grand-challenge problems, even where technologies play a considerable role. This logic parallels the decontextualized view of technology—and by implication engineers—as neutral participants in problem solving. Taken at face value, such a view actually prevents engineers from assuming a significant role in social problem solving, since the non-technical dimensions that direct (neutral) engineering would necessarily be rendered irrelevant to how engineering was applied. Only by reversing this logic—and reflecting on engineering's liabilities in producing sociotechnical challenges—can engineering be cast in a way that is more than tangentially relevant to the tackling of these challenges.

Unlike *Grand Challenges*, *The Engineer of 2020* frankly admits that, in addition to its benefits, "there have also been negative results of technology."[41] By itself, that recognition directs attention to the question: "How can engineers best be educated to be leaders, able to balance the gains afforded by new technologies with the vulnerabilities created by their byproducts without compromising the well-being of society and humanity?"[42] However unlikely it may be that the authors of *Grand Challenges* would disagree with such a statement, the report nevertheless carefully and systematically avoids recognition of any such tradeoffs surrounding technology or in current approaches to engineering. In our assessment, taking responsibility for negative consequences caused by prior technologies does not harm engineering's credibility. To the contrary, recognizing the mixed consequences of technological endeavors benefits the profession by helping to set more realistic goals when addressing complex problems and by reminding engineers (and others) of the need for caution and humility.

Grand Challenges **and Engineering Education**

As mentioned in the introduction above, the *Grand Challenges* approach has been taken up enthusiastically by several engineering education programs, which we see as a mixed blessing. Insofar as engineering students are trained to address significant social problems and insofar as they are inculcated to value a model of engineering that places public service as a central goal, students, educators, and the public are all likely to benefit. But insofar as engineering students are led to embody the contradictory assumptions embedded in *Grand Challenges*, such an initiative does them a disservice, not least through replicating naïve distinctions—between good and bad applications of engineering expertise, between the technological elite and the impeding public, between the "pure" technical and the ("polluted?") social facets of engineering practice. Such distinctions may be useful for propping up engineering's legitimacy in the face of public scrutiny, but they carry with them liabilities for engineering that do more to exacerbate grand-challenge type problems than ameliorate them.

How might educators prepare engineering students for an uncertain future, one in which engineering practice inevitably will be different than it is today? *Educating the Engineer of 2020* gives one answer: Educate engineers to be "lifelong learners." Although the term has become cliché over the past decade, as with clichés generally the underlying concept has merit: Engineering students can be trained to respond dynamically to complex, and currently unknowable, future challenges. This model of education is the opposite of “plug and chug” problem solving, and is evident in a range of experiments in engineering pedagogy, including critical pedagogies,[43] problem-based learning,[44] sustainability,[45] and interdisciplinary design initiatives.[46]

In order to educate engineering students to be active learners throughout their lifetimes, it is important to impart the habit of open-minded inquiry and the courage to challenge conventional thinking, including especially that within their own disciplines. For example, if students are encouraged to question narrowly defined technical efficiency as the predominant indicator of engineering success, they will be better prepared for aligning technical possibilities with a range of social goals and requirements. Efficiency is, of course, an abstracted index, the ratio between a given output and a given input of a particular system. Determining which particular inputs and outputs are worth optimizing (as with the question of educational context above) is a historical and situated process, usually the outcome of intensive and extensive contentions and negotiations by stakeholders, fraught with trade-offs, and suggestive of groups of winners and losers.

Whereas improving systems efficiencies is in some respects a hallmark of engineering, little attention is paid in engineering education to the actual indices being optimized. Response time, productivity, cost are all worthy of making more efficient in general terms, but in specific evaluations, each index is abstracted from a complex socio-technical context wherein competing indicators exist. For example, is labor productivity to be measured by work-hour, by overall labor cost, or by physical work extended by laborers? By opening technical efficiency to analytic scrutiny, students might learn a more comprehensive way of planning, conducting, and assessing engineering projects. The easy distinction between technical and social facets of efficiency calculations makes little sense through the lens of the lifelong-learning framework, since the very act of determining what knowledge is appropriate in a given situation demands a complex mix of skills: Social skills are needed to accurately interpret and then assess a given context in terms of what should be optimized and technical skills are needed to identify and assess the appropriateness of candidate techniques for carrying out that optimization. These two approaches work together in concert.

More systematic treatment of social, political, economic, philosophical facets of engineering will probably require curricular space, but it will also probably require a different curricular approach. While traditional disciplinary humanities and social science (H&SS) insights are surely important to engineers’ education, too many engineering curricula outsource such training, creating a gap between the content of H&SS learning and students’ understandings of and experiences with *engineering* (as defined by their “engineering” course instructors). *The Engineer of 2020* states: “It is appropriate that engineers are educated to understand and appreciate history, philosophy, culture, and the arts, along with the creative elements of all of these disciplines,”[47] but if all non-engineering disciplines are equally important, we are sure to provide a washed out curriculum. Instead, we imagine introductions to relevant disciplinary approaches that are targeted clearly and directly to engineering students’ comprehensive understandings of engineering. Free electives are fine for broadening students—allowing them to follow individual passions—but *a la carte* humanities and social science electives are unlikely to convey adequately the breadth of issues engineering faces as a discipline, as a profession, and as a set of practices.

Of course, we recognize the tension between the existence of wide-ranging relevant content and the limited time available in undergraduate engineering programs. One approach is to relax rigid expectations surrounding the existing technical core of engineering programs (in all sub-disciplines) to allow space for reconfiguring engineering curricula along the lines described above. Another approach, advocated by *Educating the Engineer of 2020*, entails moving toward a professional-degree model (as in law and medicine), where the engineering degree is at the master's level and undergraduate programs are understood as pre-professional training. Other approaches to enhance the diversity of engineering are worth discussing and experimenting with. For example, dual-major and dual-degree formats—where the second program is outside of engineering—require simultaneously developing competency in two different arenas, ideally in a way that treats each equally. Approaches that integrate traditionally classified H&SS content into "engineering" courses may be especially promising, because they not only increase the coverage of H&SS material, but also signal to students that the material is directly relevant to *engineering* practice.

The approach of integrating social and technical dimensions of engineering into a single course is evident in many design initiatives, and we believe design offers a unique opportunity for scaling up efforts to bridge social and technical facets of engineering *in the context of an engineering course*. Teaching engineering students to solve real-world problems via design projects may improve students' awareness of an array of contextual factors, including user needs, social and environmental costs, and other concerns affecting the scope and nature of engineering work.[48] Interdisciplinary design projects also provide opportunities for developing enhanced collaboration skills and increasing interactions between engineering students and those from other disciplines, because some "engineering" students might identify with the business side of engineering, others with the policy side, and still others with more traditional technical domains.[49]

Just as engineers should be expected to collaborate more effectively with more diverse stakeholders, so too should engineering education reformers. As *Educating the Engineer of 2020* points out, "a strategy for realigning engineering education must be developed within the contexts of understanding the elements of engineering and recognizing the importance of constant communication with the public and engineering community stakeholders on the goals of education reinvention and the value of success."[50] Engineering education is clearly relevant to stakeholders besides engineers, something politicians, business leaders, and economists all understand well. But, as with *Grand Challenges*, our call goes beyond enhancing engineering education in order to spur innovation and grow economies. Humanists and social scientists, management and entrepreneurship scholars, and the creative and fine arts all have something to offer to engineering education.

Conclusion

We share the enthusiasm of many engineers and engineering educators in redirecting engineering energies toward grand-challenge problems. But we also see these problems as an opportunity to rethink the nature of engineering and recast the relationship between engineering and society. A close reading of the *Grand Challenges for Engineering* report shows that it preserves an outdated image of engineering as separated from other domains of social innovation. This paper has identified several of those assumptions and described how they are untenable in understanding engineering generally, but are especially problematic if we are systematically to redirect engineering toward complex social problems. The paper has also identified how the technical-social division, in concert with externalization of responsibility for understanding the social, has problematic implications for engineers' collaboration with non-technical participants in problem solving. Drawing examples from *The Engineer of 2020* and *Educating the Engineer of 2020*, we proposed alternative understandings of engineering and its proper role in identifying and solving sociotechnical problems. We suggest ways of integrating these alternative understandings into the effort of reforming engineering education toward preparing engineers for a constantly changing world and the increasingly interconnected future problem-solving approaches.

Bibliography

[1] National Academy of Engineering (NAE). 2008. *Grand Challenges for Engineering*. Washington, DC: National Academies, p. 6.
[2] The second national NAE Grand Challenges Summit was held in Los Angeles, 6-8 October 2010. See http://www.naegrandchallengessummit2010.org/. The White House Office of Science and Technology Policy and the National Economic Council announced a request for information on *Grand Challenges* on 21 September 2009. This request is available online at: http://www.whitehouse.gov/administration/eop/ostp/grand-challenges-request-information. NAE Grand Challenge K12 Partners Program was launched "[t]o create an awareness of and involvement in the NAE Grand Challenges for the K12 community" (http://www.grandchallengek12.org/mission). A number of universities have joined the NAE Grand Challenge Scholars Program to prepare the next generation of engineers for solving grand challenge problems. See http://www.grandchallengescholars.org/.
3 To see how industry leaders discuss grand challenges as business opportunities, see the blog entry "You need to think of each of these grand challenges as a business," available at http://www.naegrandchallengessummit2010.org/index.php?option=com_content&view=article&id=18&Itemid=6.
[4] NAE. 2008. Op. cit., p. 6.
[5] NAE. 2004. *The Engineer of 2020: Visions of Engineering in the New Century*. Washington, DC: National Academies.
[6] NAE. 2005. *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. Washington, DC: National Academies.
[7] NAE. 2008. Op. cit., p. 1.
[8] Ibid, p. 2.
[9] Ibid, p. 2.
[10] Ibid, p. 2.
[11] Studies have shown that dust particles in nuclear fusion may pose a safety threat. See Winter, J. 2000. "Dust: A New Challenge in Nuclear Fusion Research?" *Physics of Plasmas*. Vol. 7, No. 10. Also see Sharpe, J. P.; Petti, D. A.; and Bartels, H. W. 2002. "A Review of Dust in Fusion Devices: Implications for Safety and Operational Performance." *Fusion Engineering and Design*. Vol. 63-64, pp. 153-163.
[12] Social scientists have contended the belief that technology is neutral. They have shown that some technological developments necessarily call for engineers' value choices and their usage entails certain patterns of political arrangement. See, e.g., Winner, L. 1988. "Do Artifacts Have Politics?" in *The Whale and the Reactor: A Search for Limits in an Age of High Technology*. Chicago: University of Chicago Press, pp. 19-39.
[13] NAE. 2008. Op. cit., p. 6.
[14] Ibid, p. 46.
[15] See, e.g., Eberly Center for Teaching Excellence's "Teaching Principles," available at http://www.cmu.edu/teaching/principles/teaching.html.
[16] Maria Klawe identifies these same problems in a recent talk given at the 2010 NAE Grand Challenges National

Summit. See http://www.naegrandchallengessummit2010.org/index.php?option=com_content&view=article&id=19&Itemid=9&youtube=1wMjD4HWNVk.
[17] Gopakumar, G. 2010. "Transforming Water Supply Regimes in India: Do Public Private Partnerships Play a Role?" *Water Alternatives*. Vol. 3, No. 3, pp. 492-511.
[18] NAE. 2008. Op. cit., p. 5.
[19] Ibid, p. 5.
[20] Engineers' distrust of the public has a long history, with evidence dating back at least to the technocracy movement of the early 1900s. Here, technocrats—many of whom were engineers—typically framed of the public as a barrier to the social realignments demanded by technical rationality. See Akin, W. E. 1977. *Technocracy and the American Dream: The Technocrat Movement, 1900-1941*. Berkeley: University of California.
[21] The rhetoric of technology as "applied science" has been carefully examined in Kline, R. 1995. "Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880-1945." *Isis*. Vol. 86, No. 2, pp. 194-221.
[22] NAE. 2008. Op. cit., p. 2.
[23] Ibid, p. 48.
[24] Ibid, p. 48.
[25] Some engineers have tried to argue that engineering is an autonomous body of knowledge independent of science. See Vincenti, W. G. 1990. *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*. Baltimore: Johns Hopkins University Press.
[26] NAE. 2008. Op. cit., p. 31.
[27] NAE. 2004. Op. cit., p. 59.
[28] Science and technology policy scholars have advocated shifting away from approaches that attempt to eliminate uncertainties through systematic analysis and toward approaches that accept uncertainty in scientific and technological outcomes as inevitable. According to this approach, effort should be directed at identifying strategies for coping with unintended outcomes as they come to light over time. Woodhouse, E. J., and Nieusma, D. 2001. "Democratic Expertise: Integrating Knowledge, Power, and Participation." *Knowledge, Power, and Participation in Environmental Policy Analysis*. Matthijs Hisschemöller, Rob Hoppe, William N. Dunn, and Jerry R. Ravetz, editors. New Brunswick, New Jersey: Transaction Publishers, pp. 73-96.
[29] NAE. 2004. Op. cit., p. 27.
[30] Thomas Hughes has famously applied such an approach in analyzing the historical development of electric power systems in the United States. See Hughes, T. P. 1983. *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore: Johns Hopkins University Press.
[31] NAE. 2004. Op. cit., p. 35.
[32] Ibid, p. 20.
[33] Ibid, p. 27.
[34] Ibid, p. 44.
[35] NAE. 2008. Op. cit., p. 5.
[36] NAE. 2004. Op. cit., p. 48.
[37] Ibid, p. 5.
[38] Ibid, p. 35.
[39] *Educating the Engineer of 2020* falls short of our suggestion that collaboration is a two-way street; it implies that the primary goal of engineers improving communication with the public is "enhancing public awareness of engineering" (National Academy of Engineering. 2005. Op. cit., p. 27).
[40] A vast body of literature in "public understanding of science"—and a journal by the same name—has developed over the past three decades. This literature emphasizes the embedded intelligence of local communities' knowledge systems, working as they do from different perspectives and responding to different sets of variables and assumptions than outside experts.
[41] NAE. 2004. Op. cit., p. 48.
[42] Ibid, p. 2.
[43] See, e.g., Riley, D. 2003. "Pedagogies Of Liberation In An Engineering Thermodynamics Class." ASEE Annual Conference Proceedings.
[44] See, e.g., Baillie, C. "Engineering Knowledge Building: The Bridge Between Research, Practice, and Teaching." ASEE Annual Conference Proceedings.

[45] See, e.g., Baillie, C. and Catalano, G. “Engineering Decisions in the Context of Sustainability: Complex Systems.” ASEE Annual Conference Proceedings. See also, Nieusma, D. 2009. “‘Sustainability’ as an Integrative Lens for Engineering Education: Initial Reflections on Four Approaches Taken at Rensselaer.” ASEE Annual Conference Proceedings.

[46] See, e.g., Nieusma, D. 2008. “Integrating Technical, Social, and Aesthetic Analysis in the Product Design Studio: A Case Study and Model for a New Liberal Education for Engineers.” ASEE Annual Conference Proceedings.

[47] NAE. 2004. Op cit., p. 52.

[48] Design learning has been recommended as a promising paradigm for teaching engineering. See, e.g., Sheppard, S. D.; Macatangay, K.; Colby, A.; and Sullivan, W. M. 2008. *Educating Engineers: Designing for the Future of the Field*. San Francisco: Jossey-Bass.

[49] Burian and Barbanell report that a course integrating engineering and humanities content for students from multiple disciplines yields an unexpected outcome: Students from engineering and the humanities learned to analyze problems from each other’s perspective. See Burian, S. and Barbanell, E. 2010. “Hydrotopia: Integrating Civil Engineering and Humanities to Teach Water Resources Engineering and Management.” ASEE Annual Conference Proceedings.

[50] NAE. 2005. Op. cit., p. 27.