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When Students Resist: Ethnography of a Senior Design Experience in Engineering Education*

GARY DOWNEY
Science and Technology Studies Program, Virginia Tech, 332 Lane Hall, Blacksburg, Virginia 24061, USA. E-mail: downeyg@vt.edu

JUAN LUCENA
Division of Liberal Arts and International Studies, Stratton Hall, Colorado School of Mines, Golden, CO 80401, USA. E-mail: jlucena@mines.edu

This ethnographic study explores how engineering students in a traditional senior design course interpreted design assignments in terms of the engineering sciences. These students, who had been taught to value the distinction between 'science' and 'design,' tended to resist design education. They had learned to think about design as a trivial extension of mathematical problem solving. This predisposition made it difficult for activist faculty to convince students that design introduces entirely new learning issues. Although limited in scope, this study suggests that for reform in engineering education to be successful, it may need to go beyond engineering design to rework teaching in the engineering sciences as well.

INTRODUCTION: SCIENCE v DESIGN

WHAT CAN we learn from student resistance to design education? Much of the current reform effort in engineering education involves expanding and enhancing student experiences with engineering design. This emphasis derives from a sense among faculty and alumni that a pendulum that swings between 'science' and 'design' has swung too far in the direction of science. The solution is to 'achieve balance' by swinging it back [1]. This attitude focuses attention on the relative timing and quantitative mix of design and science. For example, some design initiatives expand design experiences in the first year, with the hope of introducing students to what engineering is all about as early as possible [2–5]. Other initiatives integrate design throughout the curriculum with the goal of helping students in 'making the transition from the 'seat-of-the-pants' freshman design approach to the engineering design approach required for the capstone experience and engineering practice' [6].

Finally, senior design capstone courses aim at exposing engineering students to the key elements of design before graduation [7]:

- design methods
- project management
- teaming
- engineering economics
- ethics
- risks
- professional issues.

How do students understand the distinction between 'science' and 'design'? Students entering engineering programs do not bring it in with them. It is acquired through the curriculum. Since students then spend a great deal of time learning the engineering sciences, might their understanding of the engineering method, of mathematical problem solving, condition how they understand design education and practice [8]? If so, then reform in engineering education may have to go beyond swinging a pendulum, expanding and enhancing design education, to altering the meaning of the distinction between 'science' and 'design' itself. Such would necessarily involve reforming pedagogy in the engineering sciences as well.

To make more visible student interpretations of design, we conducted an ethnographic study of two traditional capstone courses in senior engineering design. This study is part of a larger project examining how learning mathematical problem solving in engineering education challenges and shapes students as people (see [9] for some preliminary findings). This paper reports findings from one of those courses, in which an activist design faculty member struggled to convince students that design was something more than a simple extension of the engineering method. Although the students involved had arrived in college with radically distinct expectations about what it meant to do engineering, by the time they reached Senior Design they knew that the engineering

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sciences were fundamental, that design was a subordinate downstream activity, and that their main task in Senior Design was to get through the experience with a minimum of stress and effort.

CURRICULUM REFORM FOCUSES ON DESIGN

As the Cold War was drawing to a close in the 1980s, the dominant American image of international relations shifted from a political-military image of struggle between Capitalism and Communism to an economic image of competitiveness among nation states. In the early 1980s, Japan appeared to be emerging as a major threat to the economic well-being of the United States. Japan's great strength appeared to lie in manufacturing, in a national ability to bring ideas to market. This ability in turn appeared to derive from a distinct cultural commitment to collaboration, manifest in a close working relationship between government and industry. American reactions to this perceived threat focused, in sequence, on technological automation bringing together design and manufacturing, joint ventures bringing together government, industry, and universities, the restructuring of corporations from bureaucracies into flexible structures built around systems of production (e.g. TQM).

In the midst of the new logic of competitiveness, two different reform movements emerged among engineers in the United States. The first, initiated during the mid-1980s, could be labeled 'The Problem is Numbers'. A key founding document is the *Engineering Deans Task Force Report* of 1989 [10]. Its main argument is that the United States needs more engineers to compete economically with Japan and other countries. Action is needed because not enough white males will be available to become engineers. Engineering schools must dramatically expand their efforts to recruit and retain women and underrepresented minorities.

The second reform movement, initiated in the 1980s in the wake of corporate restructuring, could be called 'The Problem is Inflexibility'. A founding document is the manifesto of sorts by Bordogna, Fromm, and Ernst [11]. This movement merges together two distinct concerns. The first is that the rapidly changing economic scene offers new opportunities for engineers to exercise national and global leadership. The second is that rapidly changing corporations need more flexible people to go with their more flexible organizations. Both concerns fueled an interest in curricular reform.

The two movements converged in the National Science Foundation's multimillion dollar funding of eight coalitions of schools to develop and implement models of reform, as well as numerous other efforts funded by engineering foundations or the schools themselves. While efforts in the first movement focused on new administrative programs for recruitment and retention, efforts in the second focused on curriculum. In addition, while the coalitions were underway, they became subject to an emerging interest in instructional technologies that was sweeping the academy more generally [11]. A rough idea of these emphases can be gained from the publications of coalition members. A cursory review of 554 publications listed at the websites of the ECSEL, SUCCEED, Foundation, and Gateway Coalitions indicates that:

- Over half, or 284, reported innovations in design education.
- Of the rest, 110 publications involved building links with other disciplines, e.g., economics, biology; 65 involved adding software for analysis, simulation, and optimization to existing courses; 44 involved building links with industry, e.g. internship activities; and 51 pertained to an assortment of other activities, e.g. assessment, ABET.
- Of 435 publications dealing with pedagogy, or 'knowledge delivery,' 238 pertained to computer-enhanced learning of various sorts while 51 involved laboratories and other hands-on activities, 46 involved teamwork and network building, 42 involved faculty development in teaching, and 58 reported an assortment of other activities, e.g., delivery assessment, strategies for active learning.
- Of 152 publications dealing with the underrepresentation of women and minorities, 36 reported results from pipeline studies while 116 focused on programs for recruitment and retention.

ETHNOGRAPHIC MAPPING

In both this article and the larger project, we are attempting to examine and describe the dominant tradition in engineering education from the students' points of view. (Accordingly, we introduce faculty points of view only to help describe and illustrate the dominant image of engineering pedagogy and problem solving. We do not in this work attempt to make visible the many ways in which engineering faculty enhance, resist, trouble, or otherwise struggle with the dominant model.)

Most assessments of design courses include student evaluations to determine whether ABET outcome criteria are being met. Most data are collected in survey form and tabulated numerically. In some cases, assessment includes team evaluations and written essays, and could be as detailed as to include assessment of project selection, use of skill sets, team dynamics, faculty mentoring, and project reporting [12–14]. These approaches to assessment using student evaluations help achieve accreditation and ensure that engineering graduates possess engineering design skills. However, such evaluations are not aimed at showing how students might experience design in relationship to other forms of knowledge and practice, in particular the engineering problem solving they encounter and learn in engineering science courses.

Conducting ethnographic study is an exercise in making visible experiences that get hidden. In this case, our task is to make visible patterns in student experiences with the dominant model of engineering problem solving. Conducting intensive ethnographic research for two years at a land-grant university, our project team produced 4000 pages of transcribed and coded data drawn from year-long, bi-weekly interviews with 12 focus groups, 61 individual interviews, 13 undergraduate engineering courses, and assorted presentations and lectures. (We collected these data during the period 1992–1995, before many of the Engineering Coalition reforms were developed and implemented. We maintain that these data continue to map the dominant pattern.)

Ethnographic study can be seen as an exercise in mapping. Consider, for example, how one assesses the value of a topographical map. To check for the plausibility of a map, one cannot pick up a telephone and dial a 1–800 number to reality. The only way to check the map's plausibility is to test it against other maps and mapping activities, e.g., walking the area, appealing to satellite data, etc. In other words, the interpretations in a map can be judged only in relation to other interpretations that we have come to trust as accurate and true. Accordingly, the ethnographic map gains in plausibility to the extent that it fits other interpretations that we have accepted as true. An ethnography that contributes successfully to learning might also lead us to redraw some previous maps that we had taken for granted. Such is possible only if the ethnography includes enough information about the case to allow readers to test alternative interpretations, and then reject them in favor of the one presented.

A key limitation in a poor ethnography is that it does not map the arena sufficiently. That is, it unnecessarily excludes one or more key perspectives, the inclusion of which would significantly shift the resulting interpretation. Accordingly, the value of a good ethnography depends less on the size of a sample and more on its effort to identify and locate all the key positions or perspectives that operate in the arena being analyzed. As you read the interpretation in this account, please keep in mind the questions: Are we mapping the field successfully, and sufficiently?

MAKING THE SELF INVISIBLE IN PROBLEM SOLVING

Students learning engineering problem solving experience a challenge to make themselves invisible in engineering work. (We make this argument in [9]. We outline its main features here, but do not have space to provide supporting evidence from interviews and participant observation.) In contrast with problem solving in physics, where the objective is to demonstrate that one possesses unique genius, indicating that one is another Einstein, the main responsibility in engineering problem solving is to keep one's self out of the process, acknowledge the prior existence of an established method, and prove you can do it too. Students experience this responsibility as a series of challenges. (There are many variations in the following sequence. Yet we maintain they are variations on a common theme, with differences to be understood in relation to the norm we outline.)

The first challenge is to develop right habits, for one of the initial things students encounter is a demand for discipline. An associate dean of engineering was emphasizing the importance of self-discipline at Freshman Orientation when he told incoming would-be engineers and their parents that 'engineers have to learn how to have fun . . . efficiently'. Key elements in developing right habits include using mechanical pencils, lettering properly, using engineering paper properly, expecting quizzes at any time, etc. Even engineering ethics, as it is located in the traditional model, is about disciplining the body appropriately. That is, in order to solve problems properly, one must behave ethically.

Disciplining the body appropriately positions one for the next challenge, internalizing the engineering method. The engineering method follows a strict five-step sequence: Given, Find, Equations, Diagram, Solution. The student starts by pulling Given data in numerical form from a narrative description of the problem and then decide what to Find in order to solve the problem. Then invoking established Equations and drawing an idealized visual Diagram of the various forces or other mechanisms theoretically at work in the problem, the student systematically calculates the Solution in mathematical terms. During the undergraduate years, engineering students solve thousands of problems either on paper or in programs, each time drawing sharp boundaries around the problem, abstracting out its mathematical content, calculating answers in mathematical terms, and then applying the numbers back to the original problem as its solution. They know to keep any feelings they have about the problem out of the process; these are irrelevant and can only get in the way.

The next challenge is to cope with a loss of romance. Rigorously internalizing the engineering method often conflicts with the romantic fantasies that draw students into engineering in the first place. Visions of helping society by designing new technologies or otherwise being successful in life generally include a heavy measure of agency, even autonomy. Yet, to be a successful student in engineering, one must yield autonomy to the authority of the engineering method. Learning engineering is as much a body problem as a head problem, and images of autonomy tend to dissolve away over time. Sooner or later each student is forced to face the question: Does this body fit into engineering? The curriculum itself provides the primary indicator of fit though grades, as test after test and course after course rank each student on a linear scale.

By the time students reach their junior year, the vast majority have found strategies for accommodating their bodies and minds to engineering problem solving. They had survived the solitary struggles of the first two years, adopted a range of strategies for getting through their courses, and now know they can become engineers. They have also come to relate to most instructors narrowly as functionaries who simply transmit the knowledge students need on tests. Engineering instructors are not to serve as independent sources of reflection and interpretation. Students know the curriculum was established by some past authorities and the truth or validity of its knowledge is no longer subject to question or reflection

One cost in tackling more complex mathematical challenges and gaining greater control is a sense that the rain never stops. The lonely experience of isolated struggle in the early years of engineering education gets replaced by a more shared struggle just to get through whatever comes next. When we asked upper-class students how they were doing, we often heard variations of the simple mantra, 'Eat-Sleep-Study.' We heard all sorts of strategies for doing group work, including what makes good study partners and when group work helps the most or gets in the way. We followed one organized trio of students who divided up their three toughest courses in order to conquer them together. Each did the homework for one class and prepared the others for the tests.

In sharp contrast with the entering student, the engineering graduate who emerges from the curriculum is understood to be a disciplined, knowledgeable, and powerful person, at least in terms of engineering problem solving. Knowledgeable students have gained control over mathematical idealization in a way that is unavailable to other persons, whether human or corporate. As students reach the last year, have one foot in and one foot out, and look for work, they live their grade point averages to an extent they could only imagine earlier. In a profession that does not make graduate school a prerequisite of employment, one's value as a potential employee depends in the first instance on the grade-point average that positions students in a ranked list. GPA is the key line in every résumé.

Having accomplished mathematical problem solving and wondering how to apply their knowledge to the real world, these are the students who come to Senior Design during their last year.

LEARNING SCIENCE v DESIGN

Incoming engineering students typically do not understand the engineering distinction between science and design. Many do appear to view design as the main output of engineering education, but by design they mean the ability to control technology, to create by translating one's internal knowledge into object form. Their fantasies thus fall along the lines of the stereotypic architect, whose designs are thought to be a deep, personal expression of some distinctive perspective, subjective orientation, or emotional reaction by an autonomous agent, the creator. For example, first-year students meeting in small group interviews regularly described how they long 'to design something'. Said one: 'I want to be the person that draws it . . . that kind of designs it in a way, and then hands it to somebody else and they go do it.'

The science-based engineering curriculum tells them, however, that engineering design is simply an extension of the engineering method into a messier world. It is the timely, disciplined application of mathematical engineering problem solving to real-world problems. This shift is profound, for through it the genius of design is moved from the creator to the authoritative method, from the person to the discipline.

Thus locating design downstream of science-based problem solving can produce a hierarchy that may be reproduced regularly and routinely in the traditional curriculum. Students may come to know that the engineering sciences are fundamental and that design is both subordinate and dependent. Meanwhile, the engineering sciences, in this model, have to compete with only one another. Such devaluing of design may, in fact, be what has made design education a site for resistance and struggle by activist faculty members.

A SENIOR DESIGN EXPERIENCE

We participated in two senior design classes, one in electrical engineering and one in mechanical engineering. The electrical engineering class straightforwardly asked students to apply their scientific knowledge to solve a previously-defined problem. They were given performance specifications and asked to develop a device to meet them. We report here on the mechanical engineering course, because the instructor was a design activist who was trying hard to call attention to the limitations of science-based problem solving. (For a detailed categorization of engineering design education initiatives in the US, see [7, 15].)

A key element of this design experience was problem definition. Students were to participate in teams that had the responsibility for defining their problems. The course syllabus described the main goal as '[t]o participate in a design project in which the team members will define their problems, develop a plan of action, generate solutions using ideation techniques, analyze solution using engineering skills, select and develop the optimum solution, and communicate their solution using written and oral reports.'

Over two hundred students were assigned to teams, supervised by a volunteer advisor. While some participated on long-term car projects (MiniBaja, Formula SAE, Solar Car) or industry-sponsored research projects (Nautilus, Robot Vision, Bioconverter), most joined unfunded projects that interested advisors (Vibrations Demo, Water Brake, Bike Frame, Solar Boat, Hybrid Power, Methanol Converter, and Handicapped). Student teams were to meet with advisors for 90 minutes per week, and average 6 hours of work per week developing their designs. Each team was to produce a detailed Product Design Specification as well as keep log books and produce progress reports and final oral and written reports. We were assigned to Team 19 (of 35 teams total), which included Dan, Thuy, Jen, and Deepak. (Each of these four students had come to engineering education with a distinctive take on engineering science and/or engineering design.)

An older engineering student, Dan had joined the Army for four years after high school. Through the GI Bill, he completed an associates degree in mechanical technology and worked for fifteen years as a mechanical inspector. Frustrated by the limitations he faced in upward mobility, Dan returned to school to complete an engineering degree. As he put it in an interview, his main love was not the engineering sciences: 'I'm more interested in the design aspect, the technical hands-on approach, than the theoretical, scientific aspect.'

In contrast, Thuy was fundamentally interested in engineering science. For her, the main focus in engineering education was quite appropriate. A Vietnamese refugee whose family had immigrated in 1985, Thuy had as a child planned to be a teacher in elementary school. It seems her father talked her out of it when she performed well in math and science. As Thuy put it, he built their conversations around scientific learning, 'My dad used to tell me all kinds of things about how things worked, like thermal shock for example.' She concluded it would be a shame not to put to use her skills in math and science.

Having been interested as a kid in fixing cars with her father, Jen had attended a Governor's Magnet School for science and technology and 'always knew I wanted to do engineering'. This attitude was solidified during her required Senior Project, when she worked 10 hours a week as an intern among civil engineers. 'You also had the option of going and working somewhere, so that's what I did. I worked at civil engineering firm.' She enjoyed engineering for the job, which she came to see as properly located within the authority structure of a firm: 'I liked it. I liked the atmosphere—the job atmosphere.'

Finally, Deepak came in without any idea of what he liked most. Born and raised in the United States, he had lived in India for six years while his father served as professor of mechanical and aerospace engineering at an India Institute of Technology. Interested both in math and science and in literature and social science, he had applied to some schools for engineering and to others for the liberal arts. Although his father finally talked him into engineering, the decision lacked strong conviction. 'My dad's an engineer. I liked math and science things. He said, 'Why don't you try engineering?' I decided, well, yeah, why not?' Now, as a senior student, Deepak was still uncertain about his interests and future.

Team 19 was assigned to 'Handicapped' [sic], supervised by Dr. Harris. The four team members were disappointed because their top choice was the Vibrations Demo. Handicapped had been second choice.

Dr. Harris was a design activist who regularly presented the design experience as something that went far beyond the engineering sciences. For him this meant freeing their minds to be able to explore problems creatively: 'I don't want them to see this project entirely through their science classes. I want them to be creative.' Accordingly, he placed great emphasis on teams coming up with three radically different approaches to the problem they identify: 'Three different designs is just a way I'm trying to force people to maybe present more than one idea, and then give an [argument] for these and a rationale for why you came up with the other.'

Retreat to ME science identities

The students in Team 19 resisted thinking about design in new ways. Having spent 3½ years mastering the engineering sciences, they had come to value mathematical problem solving and the hierarchy between science and design. They knew that design was a residual activity subordinate to and downstream of science-based problem solving. Hence, they were largely unprepared for its challenges. Following are some categories of experiences and reactions that illustrated the marginal status of design in their thinking and identities.

- *Initial confusion with problem definition*: At the outset, Team 19 had no idea what to do. Their initial meetings were filled with blank stares as they tried to figure out a pathway to a reasonable problem. Dan reported an experience with a friend who lost an arm in an accident and was disabled. To generate ideas, Deepak went to a library database and did a Boolean search of 'blind' and 'engineering'. Finally, Dr. Harris suggested they travel to the State School for the Deaf and Blind, whose Director he knew, to identify possible ideas. During a day-long experience, they found themselves focused on the problem of copying images. Specifically, could images be reproduced with raised dots, using some sort of graphical Braille?

- *Only a two-credit course:* Throughout the semester, team members reminded themselves that this course was not worth as much credit as other courses, befitting its status as something extra, an addendum to the curriculum. As Dan voiced it, the involvement required by their level commitment to design should be proportional to this curricular value: 'For a two-credit course an intricate design is not worthwhile.'
- *Avoiding designs that extended beyond the ME sciences*: In formulating three distinct approaches to copying images, team members found themselves forced to consider photoelectric 'scanning' as one alternative. It seemed a natural. They were frustrated, however, because their science courses in mechanical engineering and one required technical elective in circuit theory had not equipped them to understand the complexities of a scanner. Were they abandoning their identities? As Thuy complained at the end of one team meeting, 'This design shit has become EE.'
- *Resisting the advisor's efforts to extend them:* Dr. Harris lived his career on the boundary between mechanical and chemical engineering. In one meeting with students, he reported excitedly that different plastics respond differently to the heat in a transparency machine, which worked on a thermal basis. It had something to do with the thermal properties of the polymer. He extended this insight into a design idea: 'I would imagine that it'd be possible to get a film of a polymer with a closed cell structure where the heat would expand the bubbles . . .' But mechanical engineering students had not studied polymers, either. After Dr. Harris left the room, Dan immediately rejected the idea with considerable conviction, 'Materials . . . polymers . . . chemical processes . . . We can just eliminate that idea right off the top.'
- *The instructor is absolute:* At the same time, students had also been trained to view their instructors as the authoritative purveyors of engineering knowledge. Accordingly, when Dr. Harris told Team 19 that a polymer with a closed cell structure might be an interesting pathway to a thermal photocopier for the blind, they could not simply ignore him. The three design alternatives they reported on a progress report included Dr. Harris' thermal approach.
- *Fitting the design to the engineering sciences:* Team 19 reported both the obligatory thermal approach and the obligatory scanner approach, but of course neither had a chance. The approach they found most appealing, and which became their main object of interest for the balance of the course, drew on their knowledge of mechanical linkages gained from courses in statics, dynamics, and kinematics. The approach of choice was a somewhat clunky mechanical tracer linked to a Braille punch. This they could understand.
- *Locating the experience as a typical engineering course:* In the usual engineering course, students perform on cue, regularly turning in homework assignments and preparing for a rigorous schedule of exams. During the periods between homework and exam deadlines, they typically use the freedom to work on other courses. The senior design class constituted a dramatic departure from this experience because it asked students to establish and maintain semester-long schedules on their own initiative. Their reluctance and active resistance became apparent at the end when it was time to 'write up.' In one brief meeting of the group, Thuy asked almost rhetorically: 'Should we start writing up?' Jen bought a delay by invoking the authority of the instructor: 'Let's wait till he tells us what he wants.'

The class syllabus had announced each team should spend 6 hours per week on its project. Without anyone looking over their shoulder, Team 19 met an average of 15 minutes each week. The schedule specified a process for the disciplined production of a final report. Team 19 wrote its report in the last few days of the semester.

Avoiding incorporating design into engineering personhood

Interpreting design assignments and experiences through the lens of the engineering sciences meant that students did not have to internalize engineering design in the same way or to the same extent they had internalized the engineering sciences and mathematical problem solving.

- *No tests in design:* The main vehicle through which engineering students prove themselves is through performance on exams. Passing exams shows one belongs and locates each student along the linear scale measuring excellence as a prospective engineer, the grade-point-average. The design class did not fit this model because it had no tests. As Jen asserted, 'It's a design class. You don't have tests in a class emphasizing brainstorming and conceptualization.' In other words, for Jen, brainstorming and conceptualization fell outside of the central arena of engineering knowledge and practice.
- *Design is a trivial process:* The complexities of design decision making appear to be elementary compared to what students had experienced in the engineering sciences. For example, where engineering statics had required students to apply the single equation ⟨sum of the forces equals zero⟩ advanced engineering science courses challenged them to decide which equations were appropriate to which situations (e.g., first law or second law of thermodynamics). From this perspective, extending the engineering method into design is both a straightforward and a trivial process. As Deepak complained at the end of the course: 'What I did in class I did in [a course introducing senior students to design].

It's important to go through the design process once, but after that, it's a waste.'

- *Design is about individual choice:* To the extent that students do understand design as something more than a simple extension of the engineering method, they tend to draw on earlier knowledge, picturing it as the opposite of the sciences they have worked so hard to learn. That is, just as it is important to keep the self out of mathematical problem solving in order to avoid corrupting it, design is entirely about the self. It is about individual creativity, a capability that, although unteachable, fulfills in its application the early fantasy of autonomy. Jen was invoking this fantasy when she complained about being assigned to Handicapped instead of the Vibrations Demo: 'I always thought that in senior year you get to do the design project you wanted.'
- *Science is the foundation:* Finally, students who have struggled for years with the engineering sciences can only conclude that these provide the crucial knowledge fundamental to engineering practice. Even Dan, the experienced mechanical inspector whose love for design was paramount, asserted with confidence at the end of the course: 'You can't really design something until you have a good broad knowledge.'

Including science pedagogy in educational reform

The manner and extent to which these engineering students resisted and devalued education in design might provide some insights not only into design pedagogy but also into the pedagogy of the engineering sciences. Their experiences suggest that reform in engineering education may have to move beyond expanding and enhancing design education to address the very distinction between science and design, as this distinction has been taught and lived. Veteran engineering design educators from the University of Texas, US Air Force Academy, and MIT hint at this problem when they report that 'while applied mathematics and science courses build the students' skills in analysis, a chasm still exist in integrating and bridging the skills to bear on a design problem.' [16] Some design educators using more open-ended student evaluations (e.g., interviews, discovery sessions) have begun to discover a tension between engineering-science-based problem solving and design in students' experiences. In a senior design initiative at the US Military Academy to construct a ticket-tearing device for the mentally handicapped, the instructor reported that 'cadets expressed discomfort at not being given specific instructions and tasks by their faculty advisor at the start of the term. It seemed that these students were used to seeking an "approved solution". . .' [17].

While moving design education into first-year curricula and strategically inserting it into other points in a student's education are surely important steps to take, these do not address sufficiently the existing hierarchy between science and design. In order to rearrange it, intervention must be initiated on the science side as well, intervention that goes beyond introducing software for analysis and optimization and participating in emerging forms of instructional technologies [18].

One possible approach to rethinking the pedagogy of the engineering sciences is to begin with recognition that engineering is always problem solving with people. That is, engineering practice necessarily involves working and engaging in problem solving with others who define problems differently than one does. From this point of view, fundamental knowledge in engineering consists not only in mathematical problem solving with a well-defined boundary, but also involves successfully engaging in problem solving when the problem itself is defined differently from different perspectives. This means building into engineering education the humble, and yet profound, insight that, in becoming an engineer, one is developing a perspective.

At present, a key feature of engineering pedagogy is that it focuses attention entirely on developing knowledge in the individual student, apart from others. Just as the mathematical problem solver is told to start by drawing a boundary and then to live entirely within that boundary, the traditional approach to engineering design extends that boundary solely into the realm of individual creativity, into 'brainstorming,' and 'conceptualization'.

Given this emphasis, when students come together to work in teams, for example, they tend to interpret the task of teamwork as efficiently dividing labor. The team serves simply as the group analog of a person. Exhibiting this tendency, members of Team 19 simply decided who would do what task. They never expected that different perspectives might live within the group, perspectives that might need to be negotiated or require compromise. The literature on design education initiatives clearly reveals an emphasis on developing group-dynamics, time management, presentation, and leadership skills while neglecting the discovery and analysis of different perspectives in the group or, better, practice at listening to and valuing perspectives other than one's own (see for example, [5, 12, 19]).

Given this focus on them as individuals, students tend to understand design work as benefiting a uniform and undifferentiated set of users, in this case 'the blind'. Team 19's product design specification, for example, was required to include the following categories: performance, cost, market constraints, reliability, safety, aesthetics, ergonomics, life in service, maintenance, manufacturability, shipping, and testing. Students never expected that these different categories might actually map onto different groups on the job holding different perspectives.

Engineering students who are soon to graduate are probably not lacking in anxiety. They know they are on the verge of entering a world in which they become visible as people who have to work with other people. Confident in having a solid base of mathematical knowledge, Team 19 members wondered and worried about another marginal activity that tends to get located as a skill-set: they wanted 'people skills' or 'communication skills'.

Yet for engineering students, communication skills are about presentation. For example, Dan reported an early experience on the job where he was asked to present his ideas to his colleagues. He thought it would be easy, until he was on the spot. Explaining oneself to others was far more difficult than he expected. Students' understanding of people skills or communication skills are rarely about listening, about encountering perspectives other than their own and figuring out how to work with them. They do have some sense that more is involved in working with other people. Jen shared a story of a student who didn't get a job because he came across as a 'know-it-all'. However, engineering students develop no resources for conceptualizing or implementing an approach built on listening rather than on presenting.

To help students locate themselves in a globalizing world filled with different perspectives on engineering problem solving, we have developed the course Engineering Cultures (www.cyber.vt.edu/engcultures). This course travels around the world, examining how what counts as an engineer and engineering knowledge varies from place to place and over time. For example, where British engineers value practical knowledge, tend to work in private industry, and have relatively low status, French engineers value theoretical knowledge, seek to work in government, and constitute the highest ranked occupation in the country. German engineers take for granted that the main goal is quality, and a main ambition of Japanese engineers is to insure that their technical solutions help build harmony. After experiencing huge differences in cultural perspectives, students in Engineering Cultures are then poised to examine and appreciate differences that live in the history and present-day life of engineering in the United States, e.g., disciplinary differences. Indeed, the tension between design and science in the American tradition is the latest instance of an immanent tension between British and French contributions to American engineering.

A second, more far-reaching and, hence, more difficult step is to teach the engineering sciences as different worlds that engineers enter to address and solve their problems. Each of these worlds has a distinct set of mathematical elements and constraints, and it intersects incompletely with other such worlds. Bucciarelli's term 'object worlds' can serve usefully for this purpose [20].

Although we have not yet designed an appropriate experiment, we speculate that teaching the engineering sciences as separate worlds might help faculty and students come to see students within a major as internally diverse rather than as seeking uniformity through a disciplinary label. Such would enable both faculty and students to see students in the same way faculty see themselves, as specialists in one area or another. Such might also challenge faculty to bring into their classrooms the passion they exhibit in faculty meetings. That is, as an integral part of teaching the scientific material they would have to defend it, to position it in engineering space, explaining what, for example, fluid mechanics might do for them and what it does not, what are its frontiers, and what it lacks. Faculty would be expected to bring their personal experiences and knowledge into the classroom rather than feeling constrained to confine themselves only to the mathematics.

In a pedagogical world where engineers come to see engineering as 'problem solving with people', in which fundamental training in engineering includes the expectation of working with people who define problems differently than one does, the distinction between science and design would not disappear but would certainly gain different meaning. The two activities would appear as equally important dimensions of what counts as successful engineering.

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Gary Downey, professor of Science and Technology Studies at Virginia Tech, Blacksburg, Virginia, has taught engineering students for twenty-one years. He received a BS in Mechanical Engineering from Lehigh University and a Ph.D. in Cultural Anthropology from The University of Chicago. Dr. Downey is the author of *The Machine in Me: An Anthropologists Sits Among Computer Engineers* (Routledge). With Lucena, he is co-developer of the multimedia textbook *Engineering Cultures (www.cyber.vt.edu/engcultures)* and is co-authoring the ethnography of engineering education, *Just Tell Me What the Problem Is: The Making and Re-Making of Engineers.*

Juan C. Lucena is Director of the McBride Honors Program in Public Affairs for Engineers and Associate Professor at the Liberal Arts and International Studies Division (LAIS) at the Colorado School of Mines. Juan obtained a Ph.D. in Science and Technology Studies (STS) from Virginia Tech and a MS in STS and BS in Mechanical and Aeronautical Engineering from Rensselaer. Currently, he is researching how images of globalization shape engineering education, hiring practices, and engineering practices and designs under a NSF CAREER Award titled Global Engineers: An Ethnography of Globalization in the Education, Hiring Practices and Designs of Engineers in Europe, Latin America, and the U.S.