Learning Engineering: Design, Languages, and Experiences*

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ABSTRACT

This paper reviews current concerns about engineering education. Paying special attention to the role of design, constructs and themes are offered as enabling perceptions of how students can learn engineering. The constructs view the curriculum as a sum of skills to be mastered and experiences in which to be involved. The themes capture three attitudinal paradigm shifts: changing the balance between design and analysis; more explicitly recognizing that many languages are used in engineering; and considering whether the BS degree in engineering might be uncoupled from its role as the entry-level certification for the profession.

I. ENGINEERING CURRICULA OBSERVED

Engineering programs look far more alike than not, even when comparing programs in civil or electrical engineering at a large state university to Harvey Mudd's non-specialized program. These curricula are highly constrained, so significant change is hard to envision or implement.

First, our curricula are very structured, locked in to long, serial course sequences. They reflect a building-block approach to learning "everything an engineer needs to know," but they inhibit flexibility and support the student-held view that curricula are made up of disjoint and unconnected barriers, like a set of track hurdles scattered at random over a field.

Second, our curricula are institutionalized within an engineering *science* model of engineering and delivered within academic cultures that conform to a scientific research enterprise. The first two years, which are the starting points for many of the serial sequences mentioned above, are taught by other departments (e.g., mathematics and physics). They should focus on initiating engineers, but the faculty teaching these courses often have agendas quite different from those of the engineering programs they purport to serve.

Third, many engineering students believe that mathematics is *the* language of engineering, in large part because we use mathematics as the dominant means of formulating and solving problems. It is also due to the preeminence of engineering science courses in our curricula.

Fourth, we seem to do a much better job of teaching analysis than we do design.Since both analysis and design are absolutely essential to engineering learning and engineering practice, mightn't we move toward a more explicit role for design as being what engineering is all about?

Fifth and last, we conduct the engineering learning enterprise in a style that assesses each student's performance individually, thus encouraging students to see themselves as competing with their peers. This style starts before college, in K-12, and has roots in the tradition of the teacher as the authority, the source of knowledge. Industry would like us to change that.

II. ENGINEERING CURRICULA OBSERVED: A DIFFERENT CONSTRUCT

Curriculum discussions are all too often cast in terms of topics and texts that students should know. We compile lists of subjects and courses that students must take. Courses are generally given as lectures, although our laboratory courses suggest that students learn a great deal at the bench.

Are we specifying too much content, especially as the half-life of such topical learning gets shorter and shorter? Do students learn effectively in a structure whose paradigm is inherently passive? It is instructive to view engineering curricula as combining a set of skills that students should acquire and a set of experiences they will encounter as students. Using the equation as metaphor, "An Engineering Program = Σ (Skills + Experiences)," curricular discussions would first focus on specifying the skills that a student can learn— rather than the topics that she must "know"— and then on identifying those activities that a student will experience in school. The skills to be mastered are readily linked to objectives that must be met and needs that must be served, as well as to changing knowledge bases. They also make it possible to: acknowledge the effects of newer tools and approaches; import knowledge of how tasks are performed in practice; and recognize connections to other aspects of a problem-solving task that involve different disciplines or subdisciplines.

The lists of skills and experiences derive from statements of what we want engineering graduates to be able to do. Instead of listing required courses for structural engineers (e.g., Strength of Materials, Introduction to Structural Analysis, Steel Design, and Finite Element Analysis), we say that a student must be able to design a simple steel building. This means he must be able to identify

- building loads and any environmental forces;
- relevant building codes and requirements;
- basic structural choices for framing and layout;
- structural elements and their models;

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• techniques for analyzing the structure; and so on.

We see also that a student designing a simple steel structure must have learned to: read and interpret codes, interact with architects and foundations engineers, and analyze beam and column elements with a standard computer package. This produces a different set of specifications than the standard course list for structural engineers. It exposes the fact that applying qualitative knowledge about structural behavior (e.g., when deflections are too large, when "I-beams" are beams and when they are columns) may be a better skill for structural design than solving beam equations. Similarly, knowing how to correctly interpret results obtained with a standard numerical package for boundary conditions and loads that are highly-idealized may be a more valuable design skill than being able to write a meshing program. Such reconsideration of objectives might also indicate a need for participating in and experiencing team-done projects, and for attaining the ability to do design in a broader context.

Note, too, how naturally the experience requirements emerge from the answer to the question about what we want graduates to be able to do, that is, to responding to a functional specification of what we require of an engineering graduate. Faculty at all kinds of institutions should be thinking about those experiences that their students encounter because they form the ultimate justification for residential colleges and universities. Faculty must be able to say why students need to be on campus at all.

III. Design and the Analysis –versus– Design Divide

Design, a subject that is constantly being studied and analyzed, has been identified as the distinguishing mark of the engineering profession.[1] It has also long been a "hot button" in engineering education discussions. Faculty and practitioners continue to be concerned that design is neither properly taught nor adequately presented in engineering curricula. As ABET[2] and the professional societies[3] push for more design in the curriculum, there is still resistance to incorporating more design in the curriculum: "The age of engineering science is not yet over[4]."

Part of the problem derives from the engineering science orientation of the engineering educational endeavor. Most engineering faculty have spent their professional careers teaching. Most are uncomfortable teaching design because they have little direct, personal experience doing design. While many faculty consult, they generally are not designing a device to meet a client's needs under a variety of constraints.

Design was traditionally taught as a creative activity that could only be learned experientially. Design faculty did not articulate to the engineering science faculty what it was that they were teaching in design courses, so these "analytical types" felt that there was no "real" content in design education. This situation has changed significantly over the last decade or so because design has come to be viewed as a cognitive activity that can be modeled, albeit in terms other than classical applied mathematics. Design research and design itself are now taken much more seriously as legitimate areas of intellectual inquiry.[5]

The first *attitudinal paradigm shift* proposed is toward more explicit recognition of design as both the distinguishing feature of engineering practice and as a motivating factor in the learning of engineering. Simply put, beyond being the "capstone" of engineering education, design should be the very *cornerstone* of engineering learning[6] or, in an anthropomorphic metaphor, design should be the *backbone* of engineering curricula. It should be present throughout the program, in each and every year. Freshman design courses are becoming more established and their popularity is spreading.[4, 7–10] Further, in addition to those for capstone design courses[11], texts are emerging at the freshman level. [12]

When taught in a project-, team-based approach, design addresses many of the critical observations outlined earlier. In the freshman and sophomore years it connects incoming engineering students to their engineering mentors, who are seen as coaches and facilitators, and to their engineering ideals from the very beginning. It helps engineering students develop skills in some of the related "arts" of being an engineer, including working in teams, making presentations to a variety of audiences, and managing design and engineering projects.This approach also reflects the reality that few engineers work as single contributors any more, if indeed many ever did. The functional and geographic dispersion of engineering knowledge and engineering projects and tasks makes the ability to function in a team an essential part of being a successful engineer.

This is not a call for a wholesale replacement of analysis courses with design courses. Analysis and design are both absolutely essential, both for engineering learning and for engineering practice. The cornerstone notion is a change in attitude toward a more explicit and visible role for design as being "what engineering is all about." Analysis unquestionably retains its centrality for formulating and modeling engineering problems, and for evaluating design results. The point is that students have to learn engineering science so that they can do design, that is, engineering science is taught to enable our students to be able to do design.

IV. Languages (and Computing) in the Engineering Curriculum

For the last fifty years, mathematics has been the language of engineering. This is due in part to the central role of mathematics as described above. In addition, mathematical content was seen as the guarantor of suitable rigor both for research and for teaching.

However, engineering faculty know that much of what they really know cannot be expressed in mathematics alone. There's no question that we use graphics and pictures. We also use a lot of words, although often in a very structured way (e.g., in specifications and codes, in heuristics and rules of thumb). And designers and modelers of cognitive design processes certainly understand that there are many languages of design.[5, 11] But this awareness has not yet been fully realized in the engineering curriculum.

The proposed attitudinal paradigm shift about languages has two parts, and in this context, language is used to mean representation in the broadest possible terms. The first part of the attitudinal shift has to do with how we teach the engineering sciences. While we clearly depend on mathematics as the language for modeling and (initially) formulating problems, both students and practitioners increasingly use computing as a language for solving problems. So we need to give more explicit thought to some fundamental pedagogical issues about this substantial part of our curricula. Among the questions that we need to answer are: Does one acquire a "feel" for a subject through algebraic manipulation? Through many computer cycles? Through intelligent use of symbolic computing? Through some magical balance among these three means? While we used to train students in the arts of "feel" and intuition by having them perform a lot of routine algebra, now they are jumping early to the computer. So how and when do we teach them what to look for in computing results? How will they learn to distinguish computing errors from modeling mistakes? Again, some of this is already happening inter alia, but it must be more explicitly addressed in the contexts of the intentions and the contents of the engineering science part of the engineering curriculum.

The second part of the attitudinal paradigm shift in languages has to do with the "languages of engineering design." We recognize that design knowledge incorporates information about design procedures, shortcuts, and so on, as well as about designed artifacts and objects and their attributes. Further, designers think about design processes when they begin to create sketches and drawings to represent the objects they are designing. Thus, a complete representation of designed objects and their attributes requires a complete representation of design concepts that are less easily described or represented than are physical objects. We must explicitly recognize that there are several languages or representations used in design, including[13]: *verbal* or *textual statements* that are used to articulate design projects, describe objects, describe constraints or limitations, communicate between different members of design and manufacturing teams, and document completed designs; *graphical representations* that are used to provide pictorial descriptions of designed artifacts such as sketches, renderings, and engineering drawings; *mathematical* or *analytical models* that are used to express some aspect of an artifact's function or behavior, where this behavior is in turn often derived from some physical principle(s); and *numbers* that are used to represent discrete-valued design information (e.g., part dimensions), as well as continuously varied parameters in design calculations or within algorithms representing a mathematical model.

We should also teach students that different languages are employed to represent engineering and design knowledge at different times, and that we often cast the same knowledge in different languages in order to serve different purposes. For example, fundamental structural-mechanics knowledge can be expressed *analytically*, as in formulas for the vibration frequencies of structural columns; *numerically*, as in discrete minimum values of structural dimensions or in FEM algorithms for calculating stresses and displacements; and in terms of *heuristics* or *rules of thumb*, as in the knowledge that the first-order earthquake response of a tall, slender building can be modeled as a cantilever beam whose foundation is excited. Thus, one of the consequences of design education would be to help students understand that much of what they need to know is not just a set of formulas. They must learn to apply knowledge in different forms to serve different ends, which means also that they will have to become fluent translators of engineering and design languages.

V. Breadth (and Specialization) in the Engineering Curriculum

The final attitudinal shift proposed reflects concern for greater breadth in the undergraduate curriculum, or, phrased differently, a desire to reconsider the balance between depth and breadth. However, unlike the more typical discussions along this dimension that focus on humanities and social sciences courses, the argument is for greater technical breadth that results in a better understanding of systems, and of systems of systems.[14]

Graduates increasingly pursue other careers after completing a BS in engineering, including law, medicine, financial services, and teaching in K-12 schools. Perhaps the undergraduate degree in engineering ought to be regarded as an ideal liberal arts degree for a highly technological age, rather than as the entree into the profession that it has been for so long. Perhaps we should focus on process, rather than on content. Perhaps specialization in engineering should be left until the master's degree, and the undergraduate degree should be awarded after a broad, unspecialized education in the art and science of engineering.

The point is that a broad education in engineering fundamentals—coupled with a consistent exposure to design, ranging from conceptual design and design methods in the first year to detailed, client-oriented design experiences in the last two years — produces both the environment and a motivation for good engineering work. Design is the integrator in Harvey Mudd's unspecialized undergraduate program. We have ample anecdotal and survey data from alumni that these experiences provided a framework for "lifelong learning" and from many employers that our graduates "hit the deck running" at work (and in graduate school).

VI. Concluding Remarks

Engineering curricula need not look so much alike. ABET's shift toward outcomes-oriented assessments is a welcome step in this direction, and hopefully the entire engineering profession, including practitioners, educators, and students, can work toward more universal aspirations with increasingly fewer restrictions. The construct and the paradigm shifts proposed herein are intended to help us move toward a better quality of experience for undergraduates in engineering programs.

Engineering students can do meaningful design projects in the first year, and they can have real design experiences throughout their years in school. We should recognize and articulate that engineering knowledge comes and is applied in many forms and languages. And we should recognize that breadth is likely a far greater strength than the narrowness of depth at this level of education. Finally, our curricula should reflect the fact that few people in any endeavor operate as individuals, but more as members and leaders and coaches and managers of teams. In other words, we should recognize the fact that engineering is a social activity. [15]

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15. I believe Stanford's Larry Liefer was the first to articulate this phrase.