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Freshman Engineering Design Experiences: an Organizational Framework

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ABSTRACT

Criticisms leveled at US engineering schools include: they offer too few "practical" and "hands-on" courses, students are not sufficiently schooled in teamwork and team approaches to problem solving, there is too much "compartmentalization" of engineering disciplines, and there is insufficient drilling in both written and oral communication. Other criticisms have to do with retention; too many students become discouraged in the first few terms of an engineering curriculum and because of inadequate exposure to engineering and engineering design, many switch out of engineering.

This paper looks at how engineering programs are responding to these criticisms with new and revised course offerings at the freshman level that address key issues in engineering design. These offerings give students exposure to the creative nature of engineering through design projects, hands-on laboratories and open-ended problem solving. We begin by defining engineering design, engineering design education, and the qualities expected of design engineers. We outline the reasons for the recent resurgence of freshman level design activities. Finally, we develop a framework for viewing, interpreting, and categorizing the various approaches to exposing freshman-level students to many of the key design qualities. In a companion paper we give specific examples of courses at numerous schools that span the framework of approaches.

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1. INTRODUCTION

This paper is about engineering design education, and in particular about engineering design activities at the freshman level. The ideas presented here are a result of reviewing numerous "educational experiments" that are going on around the US, many of which were funded by the National Science Foundation (NSF). A spectrum of approaches to integrating engineering design ideas, skills, and knowledge into this first year of an undergraduate degree has been considered.

The paper begins by defining a few terms (engineering design, engineering design education), before looking more specifically at freshman level design.

Engineering Design : "Engineering design is the systematic, intelligent generation[2,3] and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints" [1-3]. The purpose and motivation for engaging in engineering design are (real or perceived) human needs. The outcome of the design process (sometimes referred to as the "product realization process") is often fabrication specifications, and the creation and production of a physical artifact. Engineering artifacts range from hydro-electric dams to space shuttles to new packaging systems for instant soup.

The ABET (IV.C.3.d(3)(c)) [4] definition of engineering design adds that "it is a decision-making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective." The problems that engineering design responds to are typically open-ended and under-defined, by which we mean that, respectively: "(1) There are usually many acceptable solutions to a design problem (so uniqueness does not apply); and (2) solutions for design problems cannot normally be found by routinely applying a mathematical formula in a structured way" [2]. J. Bordogna adds, "In essence, engineering is the process of integrating knowledge to some purpose. It is a societal activity focused on connecting pieces of knowledge and technology to synthesize new products, systems, and sciences of high quality with respect to environmental fragility." [5].

The engineer who is able to effectively solve design problems "requires not just the analytical competence to size a structural member, to select an appropriate material, or to

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[2]Professor Faste of Stanford's Product Design program points out that it is not uncommon for some of the best ideas to initially be labelled as "stupid". This seems to be at odds with the notion of intelligent generation of ideas.
[3]Professor Clive Dym from Harvey Mudd College adds clarification that those doing the labelling are other than the design originator, who may not be more accepting of the definition.

determine a deflected shape, but, more importantly, the know-how to formulate a problem in a way that is in tune with the resources at one's disposal; so too it requires knowledge of fabrication techniques, a sensitivity to costs, tolerance of ambiguity and uncertainty, how to ask the right questions of a supplier and the ability to negotiate with others, even the corporate lawyer or the firm's marketing manager. Design, in this general sense, is what engineers do most of their waking, professional hours!" [5]. Design engages both the intellect and the imagination of the designer.

Many of the qualities that an engineer needs in order to work as an effective design engineer are listed and defined in Table 1. This is not a comprehensive list, and an engineer would not necessarily need all of these qualities on every job. It was compiled from numerous sources, including [3, 7-10] and the Stanford Mechanical Engineering—Design Division Retreat (March 17-19, 1995). Notice that each quality is comprised of competency and attitudes. *Competencies* are the skills necessary to carry out the mechanics of a particular quality. *Attitudes* refers to the mental position or feeling an engineer has with regard to the importance of a quality in carrying out a job, and encompasses beliefs and "buy-in." Attitudes are akin to Bloom's "affective objective" in his taxonomy of learning objectives (the other two are cognitive and psychomotor objectives) [11].

The list in Table 1 overlaps with portions of Greenfield Coalition's competency list for manufacturing engineers [12] and could be recategorized in terms of Greenfield's high-level objectives of "Know-self and others," "Solve unstructured problems," and "Lead change." Table 1 also complements the competency list recently published by Crain, et al. [13].

Thinking about the qualities needed by design engineers leads naturally into thinking about design education.

Design education: In contrast to Engineering Design, where the objective is an "artifact," design education is primarily focused on students, and on helping them understand and experience the process and methods of realizing an artifact. The quality of the student-created artifact is often of secondary importance in the learning process. Engineering educators believe that students should understand how to generate design specifications, and how to go from design specifications to a final artifact by establishing objectives and criteria, generating alternatives, synthesizing, analyzing, constructing, testing and evaluating. ABET requires that each engineering student's academic career "include a meaningful, major engineering design experience that builds upon the fundamental concepts of mathematics, basic sciences, the humanities and social sciences, engineering topics, and communication skills. The scope of the design experience within a program should match the requirements of practice within that discipline. The major design experience should be taught in section sizes that are small enough to allow interaction between teacher and student team efforts are encouraged where appropriate" [4]. The design-related qualities listed in Table 1 should be part of the major design experience.

Larry Leifer [14] offers three provisional notions of design education: that design education is a social activity, that learning (to design) requires becoming comfortable with ambiguity, and that all education is re-education. These provisional notions plus the qualities listed in Table 1 become the drivers behind the various ways of creating design experiences for freshman-level students.

2. BACKGROUND ON FRESHMAN DESIGN (1950-late 1980's)

During the period immediately following the 1955 Grinter Report [15], engineering curricula swung from a practical base to a scientific base with more emphasis on theoretical approaches and less emphasis on the "machinery" of engineering. The freshman and sophomore years, which contained many practical experiences such as graphics, manufacturing processes, and problem solving laboratories underwent major revision. Hands-on engineering experiences were replaced with additional math, physics and science courses. The upper division courses underwent similar revisions, with many labs disappearing in favor of more theoretical science courses.

In the middle to late 1960's, engineering educators began to react to the lack of understanding of design by their students. This concern produced several studies and one of the results was a recommendation to incorporate design throughout the four year curriculum. In the freshman year, the only engineering activity related to design was engineering graphics and so the burden for incorporating freshman design fell upon the few remaining graphics professionals. As a result, in the 1970's and early 1980's freshman design courses and course segments were common at ABET accredited institutions.

One measure of the design activity during this period of time was the annual Creative Engineering Design Display held at the summer ASEE meeting. Sponsored by the Engineering Design Graphics Division and the Design in Engineering Education Division, this competitive event drew many entrants from a large number of institutions. For example, in 1978, at the Vancouver, BC, meeting, there were 40 freshman, seven sophomore, four junior, 10 senior, and one graduate entrant.

At the freshman level the participants in the Design Display frequently included participants from the following Universities: Arizona State, Cooper Union, Drexel, Hofstra, Iowa State, Marquette, Mississippi State, Nebraska, North Carolina State, Northeastern, Purdue, Southern Methodist, Villanova, Virginia Polytechnic Institute, and several community colleges.

By the middle 1980's, increased pressure to include more technology in the curriculum, particularly computer-related technology, squeezed already packed curricula to the point where the freshman design courses were eliminated or scaled back significantly at most schools. In fact, interest in the Creative Engineering Design Display waned to the point that in 1987 the event was canceled.

Reference [16] by Evans, McNeill and Beakley provides a more complete account of design education history during this period.

3. BACKGROUND ON FRESHMAN DESIGN (late 1980's-present)

Since the late 1980's there has been a national movement to increase the amount of exposure undergraduate engineering students get to engineering design. This has been particularly true at the freshman level. There are a number of factors behind this movement, although it is difficult to know which of these are motivating factors and which are the products. A few are listed below:

• *Recognition of Freshman Attrition.* It is now generally accepted that the freshman year is a crucial period for engineering majors. The freshman year is the time period when attrition is high, a period in which engineering as a curriculum path is "de-selected." Seymour and Hewitt in [17] studied the patterns of students who were initially science, math or engineering (SME) majors who eventually switched out of these majors. Their work shows the top four reasons for this "de-selection":

- a loss or lack of interest in science ("turned off to science");
- believing that non-SME majors hold more interest or offer a better education;
- poor teaching by SME faculty; and
- feeling overwhelmed by the pace and load of the curriculum demands.

These reasons are in contrast with the common assumption that most switching is caused by personal inadequacy in the face of academic challenge. Several of the NSF-sponsored engineering education coalitions (e.g., the ECSEL Coalition) have focused their efforts to reduce this attrition, to enlighten students to professional opportunities, and to empower them by using “design” as an introduction to engineering.

• *The NSF Engineering Education Program* (the "Coalition" program) [18]. The principle objective of the Engineering Education Coalition program, which was established in 1990, has been to support a small number of major coalitions of US institutions in a multi-year effort to:

- increase dramatically the quality of US undergraduate engineering education;
- design, implement, evaluate, and disseminate new structures and fresh approaches affecting all aspects of US undergraduate engineering education, including both curriculum content and significant new instructional delivery systems; and,
- create significant intellectual exchange and substantive resource linkages among major US engineering baccalaureate-producing institutions and other major and smaller institutions.

The Coalition program was responding to a projected shortfall of engineers at all levels, and to a perceived need to restructure engineering education (particularly as related to scientific and technological literacy, integration of principles among different disciplines, skills in problem definition and communication, and the quality of the interaction between the students and faculty). There was also a perceived need to develop new learning environments that effectively utilize new communication and information technologies, and to heighten the role of laboratory instruction, experimentation and design. In general, there is a need to produce engineers who are more informed about the technological, environmental, global and social factors involved in engineering practice.

There are now eight Engineering Education Coalitions[4] representing some 59 Universities (roughly 20% of all of the undergraduate institutions in the United States). The goals of the Coalition program, as listed above, and the need for many of the qualities listed in Table 1 in our graduates have been underscored by the recent reports "Engineering Education for a Changing World" [19], and "Restructuring Engineering Education: A Focus on Change" [20]. Reference [19] was a joint effort by the Engineering Deans Council and the Corporate Roundtable of ASEE. It also suggests the end of the Cold War should be motivating universities to revisit their approaches to teaching engineering.

• *Industry*. Companies like Boeing are taking aggressive stands on what industry needs in future engineering graduates, the state of current education, and what cooperative roles industry and academia play in making change [8,21]. In addition, they are facilitating

[4] The URL for the NSF Coalition program is http:www.needs.org/coalition/

discussions and partnerships between academia and industry by hosting workshops between leaders in both arenas [22].

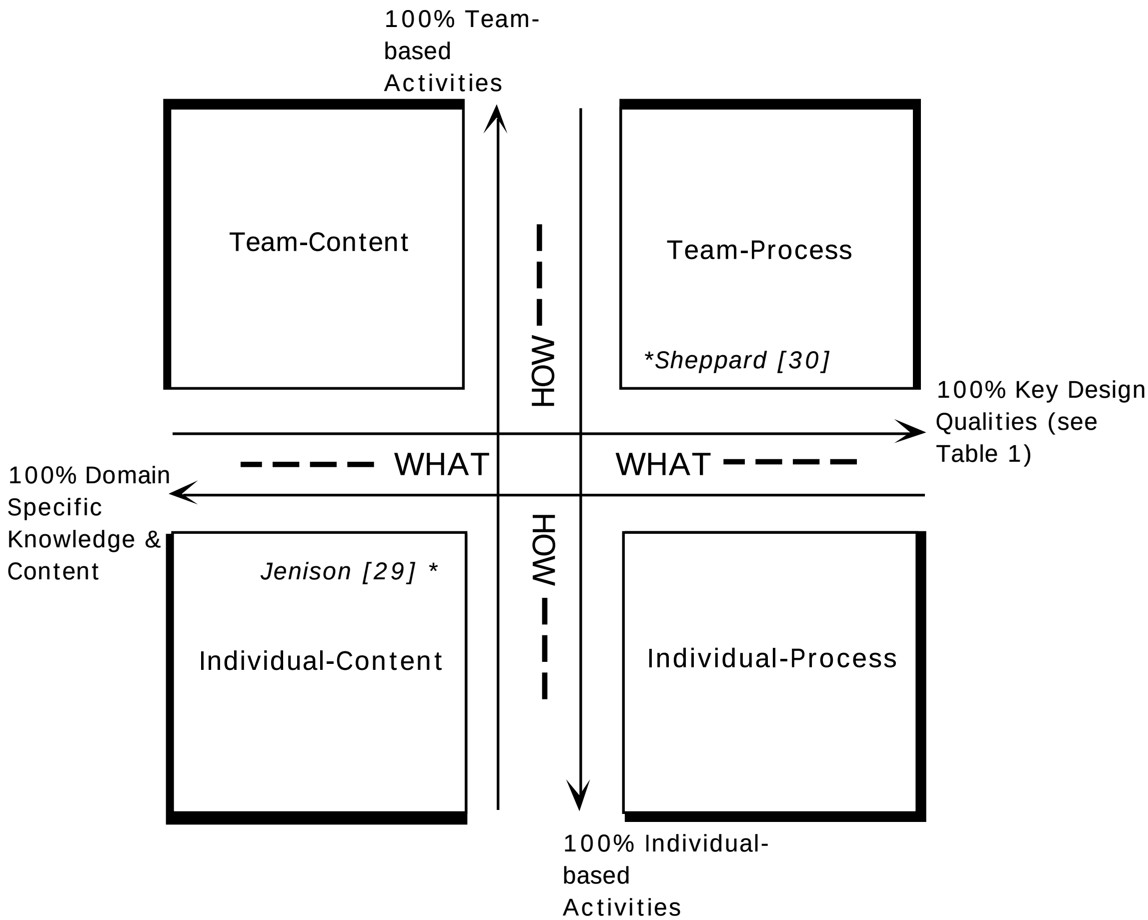
• *New ABET guidelines*, [4,10] which include a combined year of engineering topics (engineering science + engineering design). The academic career of the engineering student must still include a major engineering design experience (as discussed above) when the student's academic development is nearly complete (i.e., senior year—capstone experience). The ABET design-related criteria go beyond this—it is the institution's responsibility to articulate the goals of its program, the logic used in the selection of engineering topics to meet the goals, and identify the major, meaningful design experiences and how they are *integrated throughout the curriculum. Design cannot be taught in one course; it is an experience that must grow with the student's development.*

• *Educational Theory.* Design education, when based on open-ended problem solving and authentic projects is consistent with current thinking about learning that is held by cognitive scientists. This school of thought, called Constructivism, holds that knowledge is constructed from experience [23]. This is contrasted to the more common objective approach, where the student is viewed as an empty vessel. In Constructivism, learning results from a personal interpretation, is active with meaning developed on the basis of experience, is collaborative with meaning negotiated from multiple perspectives, and should be situated in realistic contexts. In addition testing should be integrated with the task. The growing number of Engineering-Education-related publications (e.g., [24, 25]) attest to the fact that cognitive scientists and the engineering professoriate are beginning to collaborate with one another in meaningful ways in order to create effective learning and teaching environments and experiences.

4. An Organizational Framework—pedagogy and structural differences

Up to this point we have offered definitions for engineering design and design education. As part of this a list of design qualities (Table 1) has been defined. This was followed by a discussion of some of the possible factors that have lead to a resurgence of interest in teaching design at the freshman level. We how turn to a discussion of how design might be taught at the freshman level. This is in fact a design problem "statement," with many solutions (none of which is globally best). There is a spectrum of approaches to how the design qualities listed in Table 1 can be incorporated into the freshman level educational experience. This spectrum can be organized in terms of a two-dimensional framework that reflects pedagogy and structural differences. This framework is suggested by reviewing the large number of freshman design-related activities and courses that are going on throughout the United States and is diagrammed in Figure 1.

Figure 1. A Two-Dimensional Framework for Viewing Freshman Design Courses



The horizontal dimension of the framework is related to the type of skills and knowledge that the course is primarily trying to develop in the students. The vertical dimension is related to a major element of the pedagogy (individual vs. team). We will discuss each of these dimensions in turn. While we propose a two-dimensional framework for characterizing courses, it is important to note that *all of the specific courses or course modules that will be discussed use open-ended problems in some format in order to promote the qualities listed in Table 1.*

Skill/knowledge type dimension (or, "what is taught and learned"). This dimension relates to the extent that the course is focusing on domain-specific *content* materials and skills [26], or the design qualities listed in Table 1. McNeill et al. [27] referred to these two extremes as "analysis" and "strategy development=design," respectively.

The far-left orientation of this dimension reflects courses whose prime focus is on domain-specific knowledge and content. Characteristics of these courses include: achievement of goals is measurable with conventional exams, subject matter is consistent from year to year, course is product- ("final artifact," "right answer") oriented, teaching method is instructional in nature (lecture-practice-lecture-practice), it is relatively easy to "take pulse of class" to see if they are apparently "getting it," and a textbook is generally available. Examples include traditional engineering science courses such as strength of materials, dynamics, as well as most calculus and science courses. Teslow et al. [25] describe these as "objective" courses.

The far-right orientation of this dimension reflects courses whose prime focus is helping students develop the Table 1 qualities. Characteristics of these courses include: open-ended problem solving, achievement of goals is rarely measurable with conventional exams (and may require observational methods such as ethnography or video interaction analysis [28], longitudinal "snapshots" such as portfolios, or reflective methods such as journaling), subject matter is not consistent from year to year, course is process/method-oriented, teaching method is experiential in nature (experience-lecture-exercise-reflection), it is difficult to "take pulse of class" in a quantitative manner to see if the students are "getting it," and a textbook is generally not available.

A course that is located midway between the two extremes reflects an "average" position for the course; this could mean that every homework/lecture is balanced "50/50" in terms of qualities and content material, or that the sum of all the exercises results in a 50/50 position, with some being content-oriented and others focusing on Table 1 qualities. For example, Jenison [29] developed a freshman graphics course at Iowa State University that has integrated three design projects amid a curriculum that retains a significant number of domain-specific objectives (therefore this course is located to the left of the 50/50 mark). In contrast, Sheppard [30] has created a course focused on having students explore machines and mechanisms around them. Students "discover" through hands-on labs how these machines work. Content materials are presented in support of the laboratories (this course is located to the right of the 50/50 mark).

Pedagogical Approach Dimension. The second dimension of the organizational framework reflects "how the what is taught?" This is the vertical dimension in Figure 1. This dimension encompasses the relationship between the students, the overall classroom environment and atmosphere, whether homework assignments are a collective or individual responsibility, whether work is assessed on an individual or group basis, and the extent that classroom time is used for lecturing or group work. This dimension reflects whether a student sees him- or her-self as an individual learning a body of knowledge and/or gaining competency, or as part of a team that is collectively responsible for learning, sharing and utilizing knowledge. There are persuasive arguments that can be made for both approaches; individual assignments allow for greater assurance of individual accountability and competency, while team-based learning may better reflect the work world, allows students to feel less isolated in their learning, and presents multiple representations of knowledge.

Jenison's and Sheppard's classes have been placed in Figure 1 relative to this vertical axis. For example, Jenison's course [29] uses some team-based projects, but over 50% of a student's grade is based on individual homework assignments. In contrast, over 70% of the projects and assignments in Sheppard's course are team-based [30].

Taken together, the two-dimensions define four quadrants. In a companion paper [31] we consider examples of courses that contribute significantly to students developing the design qualities during their freshman year and that fall in the various quadrants. Many of these courses are a direct result of NSF and NSF-Engineering Education Coalition funding and/or participation.

5. Conclusions and Summary

The design engineer must have a number of qualities, as listed in Table 1. These qualities can be viewed as being comprised of competency and attitudes. One of engineering education's major challenges is to help students develop these qualities in their four-year stay at a University. The trend in US Engineering Education since the late 1980's has been to start this development at the freshman level. This trend has been motivated by a number of factors which were reviewed in Section 3.

The mechanics of integrating experiences that help students to develop the qualities listed in Table 1 can take a number of very different forms. A framework with which to view these forms was laid out in Section 4. This two-dimensional framework considers the type of skills and knowledge that a course is primarily trying to develop in the students, and a major element of the pedagogy (individual vs. team). In a companion paper we give specific examples of freshman-level courses at numerous Universities that span the framework of approaches and that contribute significantly to student development of the Table 1 qualities.

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