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Examples of Freshman Design Education*

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This paper looks at specific examples of how engineering programs around the United States are revising freshman year curricula to include engineering design. It builds on a companion paper [1] which provides a framework for viewing, interpreting and categorizing the various approaches to exposing freshman-level students to key design qualities. Example courses are grouped according to this framework, and similarities and differences in approaches are discussed. The paper goes on to reflect upon some of the challenges that design education, particularly at the freshman level, present to instructors and students. These include needs for: re-evaluating the role of instructor; re-evaluating the role of students; providing students with meaningful (and 'doable') open-ended tasks; assessing student performance; and rescoping expectations of future instructors and how the freshman year meshes with sophomore activities.

INTRODUCTION

THIS PAPER presents examples of courses that give freshman students exposure to engineering design. Each of these courses aims to help students develop a subset of the design qualities listed in Table 1 and described in a companion paper [1].

The companion paper also establishes an organizational framework for presenting these design courses. One dimension of the framework is concerned with: *Skill/knowledge type dimension* (or, 'what is taught and learned'); the other dimension is concerned with: *Pedagogical approach* ('how the what is taught'). The resulting 2×2 matrix is shown in Fig. 1. The quadrants in Fig. 1 are:

- **A: Individual-content centric** (e.g., most traditional lecture-based courses fall in this category);
- **B: Team-content centric** (e.g., many traditional lab-based courses);
- **C: Individual-process centric** (few undergraduate engineering courses fall here, but many studio art courses are here);
- **D: Team-process centric** (e.g., most senior-level capstone design courses).

This paper is offered with the recognition that there are many excellent freshman-level innovative design education experiments going on across the country in engineering schools, and space prevents us from discussing all of them. The examples presented represent a spectrum of approaches and therefore serve as good illustrations.

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SPECIFIC EXAMPLES

A: Individual-content centric courses

This quadrant of the framework carries with it many of the characteristics of 'traditional' engineering science, mathematics, and science classes. But there have been significant efforts to shift the position of several of these 'traditional' courses towards a more central position, as illustrated in Fig. 1. In general, it can be said that very little explicit instruction is devoted to process-related activities, but the courses create 'experiential' opportunities. Consider first the shift in calculus that has resulted from the recent calculus reform efforts.

Calculus.

The Harvard Calculus work (also known as the Calculus Consortium based at Harvard) was funded by an NSF grant (other Consortium schools include University of South Alabama, Suffolk County Community College, University of Arizona, Stanford University, Chelmsford High School, Haverford College, University of Southern Mississippi, Colgate University). The basic principles behind Harvard Calculus are the rule of three (every topic should be presented geometrically, numerically, and algebraically) and, the 'Way of Archimedes' (formal definitions and procedures evolve from the investigation of practical problems). Emphasis is on meaning (in practical, graphical and numerical terms) of the symbols (language) being used and interpretation of formulas. Students are asked to 'Explain your ideas in words' or to 'Clarify your answer using graphs'. Success with the homework comes by grappling with the ideas of calculus, as well as working in small study groups (in fact it is

Table 1. Qualities expected in a design engineer and that engineering courses should be helping engineering students to develop.

The Engineer or Engineering Student should be able to ...
QUALITY
1. Communicate, negotiate and persuade
2. Work effectively in a team
3. Engage in self-evaluation and reflection
4. Utilize graphical and visual representations and thinking
5. Exercise creative and intuitive instincts
6. Find information and use a variety of resources (i.e., resourcefulness)
7. Identify critical technology and approaches, stay abreast of change in professional practice.
8. Use analysis in support of synthesis
9. Appropriately model the physical world with mathematics
10. Consider economic, social, and environmental aspects of a problem
11. Think with a systems orientation, considering the integration and needs of various facets of the problem
12. Define and formulate an open-ended and/or under-defined problem, including specifications
13. Generate and evaluate alternative solutions
14. Use a systematic, modern, step-by-step problem solving approach. Recognize the need for and implement iteration
15. Build up real hardware to prototype ideas
16. Trouble-shoot and test hardware

encouraged—group homework teams collaborate in completing exercise sets, and answers must be written out in complete sentences).

Products of this project include a textbook [2] and annual workshops on teaching calculus using the new approach (several of which are sponsored by royalty money, as none of the authors are receiving royalties). Many of the text example problems and homework problems are open-ended—there is more than one possible solution and solution approach. In addition, common sense ideas may need to be used in problem solving and are not necessarily stated in the problems.

The University of Michigan is one of over 300 Universities, Colleges and Community Colleges that have has adopted Harvard Calculus. In addition they have added design problems in discussion sections. *Univ. of Michigan Today* (Oct. '94) quotes a student as saying, 'I had been exposed to things like derivatives, integrals and similar calculus terms before and been able to figure them out with little difficulty. However, for the first time, I now feel that I am able to understand what these things really mean and how to use them.'

The Harvard Calculus work directly addresses qualities of:

- communicate (1),
- work effectively in a team (2);
- utilize graphical and visual representations and thinking (4);
- find information and use a variety of resources (6);
- appropriately model the physical world with mathematics (9).

The numbers refer to Table 1. The changes from a deeply entrenched quadrant A position towards a more central position in Fig. 1 framework is happening in K-12 education as well. Take as an example the new guidelines for K-12 science instruction [3].

Statics and strength of material.

Larry Bucciarelli from MIT, in his work sponsored by the NSF ESCEL Coalition, has produced a textbook and approach to teaching the fundamental concepts and principles of Mechanics of Solids built upon the importance of the vocabulary of structural engineering (*Engineering Mechanics of Solids* [4]). His goal is to get students to see the world 'from the perspective of an engineer responsible for making sure that the structure does not fail, that the mechanism doesn't make too much noise, that the bridge doesn't sway in the wind, that the landing gear does not fold up upon touch down . . .' The menu of problem types in the book include:

- *estimate exercises* (open-ended in that the student must model, and judge on their own, certain features of the problem);
- *what if exercises* (meant to provide students with a problem that is a variation on one they have previously worked or seen in class);
- *show that exercises* (that provide the student with the answer to the problem in the problem statement; construction of an argument);
- *construct exercises* (construct an explanation on the basis of analyses, data collected, talks with suppliers—e.g., construct an explanation explaining why the beam failed).

In addition, design exercises for use in homework or discussion sections are provided in the book, and as with the Harvard Calculus, collaborative work is recommended. The style and voice of the book aim to provoke the reader to consider process more seriously and in more realistic contexts (and thereby engage students in learning) and is intended to get to the 'nature of design'. Bucciarelli has created a curriculum approach to teaching the fundamentals of Mechanics of Materials that helps students 'carry knowledge ... toward creative application' (as required by the Accreditation Board for Engineering and Technology, ABET, [5]).

Bucciarelli's approach to teaching Statics and Strength of Materials is aimed at giving students experiences with a number of the Table 1 qualities. In particular, with:

- communicate (1);
- work as a team (2);
- use analysis in synthesis (8);
- model the physical work with mathematics (9);
- define and formulate open-ended and/or under-defined problems, including specifications (12);
- generate and evaluate alternative solutions (13);
- use a systematic approach to problem solving (14).

The numbers refer to Table 1.

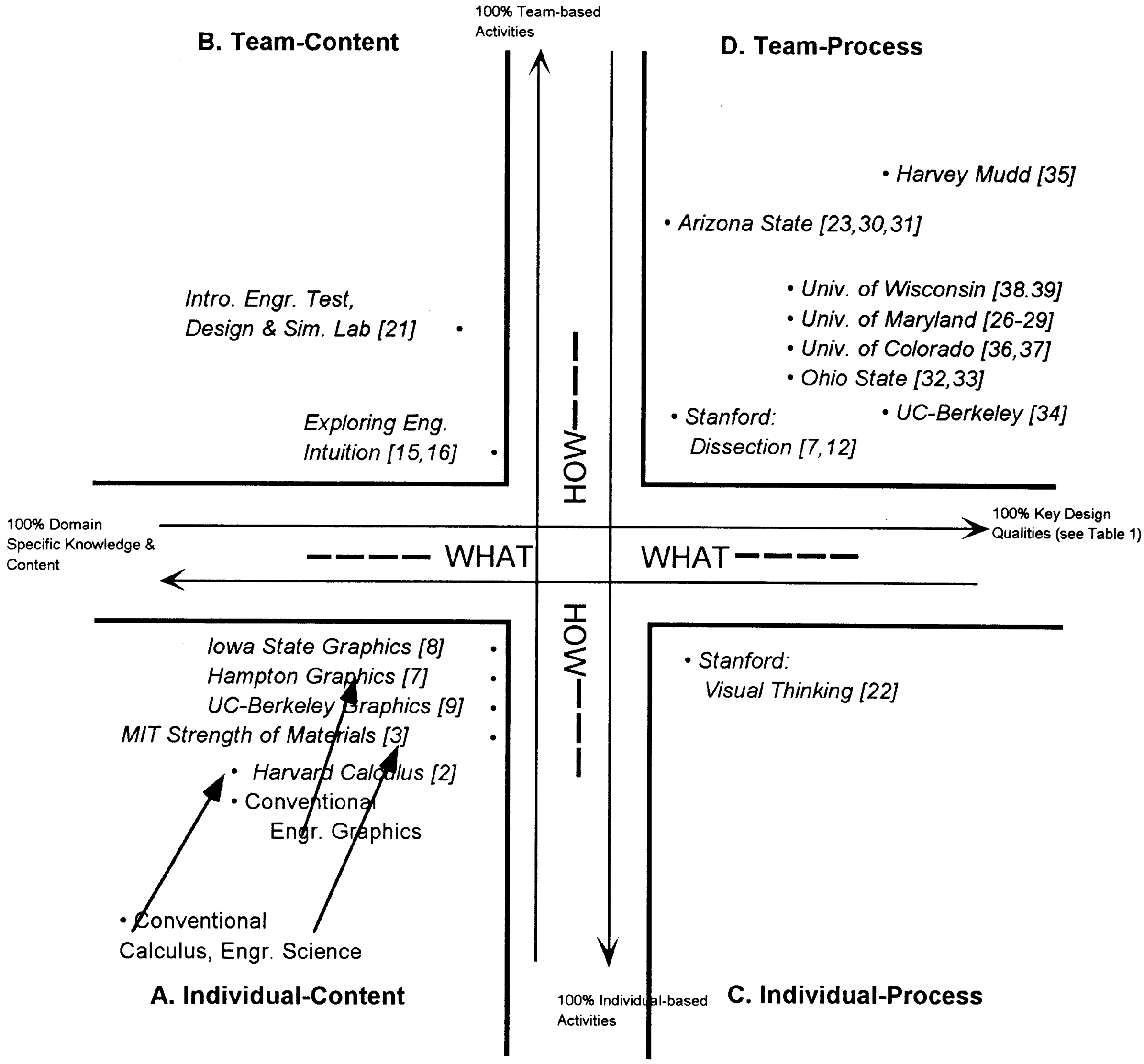

Fig. 1. The two-dimensional framework for viewing freshmen design courses, including placement of illustrative courses.

Introduction to graphics.

The intellectual basis of the curricular components in the NSF Synthesis Coalition (emphasis on hands-on experiences, increased teamwork and multidisciplinary activity, better learning environments, and real-world emulation [6]) fostered a new look at how design graphics was taught. Three graphics courses that resulted from NSF-Synthesis support at Hampton and Iowa State Universities, and at the University of California at Berkeley (UC-Berkeley) use multiple design projects woven throughout the term. Like the Calculus and Strength of Materials work discussed above, these changes in graphics courses represent a shift in position in the Fig. 1 framework. These shifted graphics courses should enable the engineering student to:

- communicate (1);
- work as a team (2);
- use graphical and visual representations and thinking (4);
- generate and evaluate alternative solutions (13).

The integrated graphics courses at Hampton University [7], Iowa State University [8] and the University of California at Berkeley [7, 9] focus on design throughout the term (like the approach taken by Larry Bucciarelli with Strength of Materials) while introducing the major aspects of graphics on a just-in-time basis. All three courses have three major projects and several individual practice exercises to develop knowledge and skills in graphics (i.e., sketching and geometric modeling capabilities) necessary to perform effectively in a design environment. Students participate in team-based projects along with individually graded homework assignments.

At Iowa State the first project, assigned on the first day of class, requires student teams to select a common household appliance such as a refrigerator, toaster, VCR, blender, etc., find out how the appliance operates, what the major materials used are, and produce simple sketches and drawings of the major parts. A brief oral report is given, thus requiring the students to produce good sketches and/or CAD drawings. During the project students are given basic instruction on sketching and the CAD software as needed. At Hampton University and Berkeley the first project involves pictorial sketching, mental rotation, and cardboard modeling. Events and synthetic environments are described verbally to students and they are asked to each provide visual representations. CAD models are then generated by students to verify their answers to questions concerning mental rotation. These spatial projects are complimented with exercises that emphasize the development of spatial reasoning skills in the context of engineering applications [10, 11]. Interactive computer-based spatial reasoning tutorials have been integrated into the class, aimed at reducing gender and perhaps minority/majority differences in spatial reasoning skills. The courseware is coupled with hardware (e.g., LEGO™ pieces) to provide both a hands-on and a virtual reality experience in reasoning spatially about three-dimensional objects.

The second project at Iowa State is a product dissection exercise, adapted from the work of Sheppard [12]. The student teams (different teams from the first project) take apart a device (e.g., a high speed rotary tool), describe the operational characteristics, operate the device for its intended purpose, and offer suggestions for alternative uses and improved design. During this process, the teams are required to prepare assembly drawings (sketches and CAD representation), create solid models of individual parts by measuring the actual part and using the CAD software. Such topics as section views, dimensioning, and multiview layouts are taught along with this project. As with the first project, graphical communication is embraced and effectively practiced by the students because it is being used to describe a real engineered product. The second project at Hampton also involves product dissection. For example, students may be asked to redesign a mechanical pencil. The work starts by having the teams take a pencil apart and then reassemble it. The thinking process of disassembly and reassembly helps the student in visualization.

The second project at UC-Berkeley combines the dissection idea with a multimedia case study of an engineered product [13]. Students are divided into teams and asked to observe an engineered product from the outside and answer questions concerning its functionality and design intent. They are then allowed to disassemble the product and asked to evaluate the design from a 'design for assembly/manufacture' standpoint. The Mattel toys are popular for this age group as they show that sophisticated engineering techniques are used for a range of commercial products, including toys. The case focuses on a toy designed for pre-school children and represents Mattel's first major effort in improving their design process to reduce assembly and manufacturing costs while maintaining or improving product quality. The multimedia case study describes the new design processes (such as computer prototyping) along with visuals (still images and videos) of the actual design team members. A walk through the manufacturing process is provided in digital video, including the use of sonic welding to reduce the number of fasteners and improved safety of the final product.

The third projects at Hampton, Iowa State and UC-Berkeley are creative design exercises. At this point in the term the students are now thoroughly familiar with the design process and CAD/sketching tools, and are eager to apply their new capabilities to a problem for which there is no unique solution. At Iowa State and UC-Berkeley this last project is also a team project and requires a written report and oral presentation, including justification, of the design solution. During this part of the course very little lecturing is done. The instructor acts as a consultant, monitors progress using team-produced milestones, and schedules appointments between teams and discipline faculty if necessary. At UC-Berkeley the third project is designed so that a final competition on performance of the design is required. Judges from industry also rate the teams on their presentations and drawings.

During the fall of 1995, an experimental version of the graphics course at Iowa State was taught with mobile robots as the 'real' product focus. The third project included a kit of parts including mechanical links, wheels, DC motors, fasteners, a microprocessor control box, toggle switches, and wiring harness were made available to the teams. A specific set of tasks were assigned and the teams applied the design process to design, build, and test devices to perform the tasks. The project included a competition with points awarded for completing the tasks and time required. This project is the beginning of a sequence of activities which expose a majority of engineering students to the use of mechatronics in engineering design. Mechatronics is the electronic control, particularly software control, with emphasis on embedded computing, of physical processes and devices.

At Hampton the third project is framed to make students form a mental picture of the object, retain the picture and manipulate it. For example, in redesigning a mechanical grinder, solutions range from replacing the material used for the crank to redesigning the mechanism with a system of gears. All solutions are eventually communicated on an instructional CAD system. It is noteworthy that one of the students from this course won a third place prize in the 1994 SilverScreen Student Design Competition sponsored by Schroff Development Corporation (5424 Martway Mission, KS 66205).

In addition to the qualities identified above for all three of the Graphics Courses, the course at Hampton University emphasizes qualities:

- find information and use a variety of resources (6);
- define and formulate open-ended and/or under-defined problems, including specifications (12).

The course at Iowa State puts particular emphasis on qualities:

- exercise creative and intuitive instincts (5);
- stay abreast of changes in professional practice (7);
- use a systematic approach to problem solving (14).

The course at UC-Berkeley on qualities of:

- exercise creative and intuitive instincts (5);
- think with a systems orientation (11);
- use a systematic approach to problem solving (14).

A similar approach to integrating design experiences into a freshman-level graphics course has been developed at Santa Clara University [14]. One major difference is that the Santa Clara course puts considerable emphasis on design presentation (using a poster format), as well as peer evaluation.

B: Team-content centric

We saw in the last section several examples of courses that introduce students to open-ended and/or design-oriented problem solving as a means of nurturing qualities in Table 1. These courses are dominated by well-defined, domain-specific objectives that have been complimented by open-ended problem solving. Collaboration is encouraged, but the majority of the student's evaluation is based on individual homework assignments and tests. In this section we give several examples of courses that, like the courses in quadrant A, have well-defined, domain-specific objectives, but that use team and group work a majority of the time.

Consider the course in 'Exploring Engineering Intuition' created by Margot Brereton at Stanford with NSF Synthesis funding [15, 16]. This class is designed to 'ground' fundamental concepts taught in analysis classes by exploring them in the context of team hardware design and dissection projects. In contrast to traditional engineering laboratory experiments designed to lead the student through a technique or elucidate a principle, this class explores simple principles from within the confusion of real context provided by products and design projects. Students learn embodiments of fundamental principles, such as how castings are stiffened. They get a feel for typical quantities such as the power ratings of various products. They learn what components look like and terminology for describing them. They get experience devising their own strategies for what to measure or how to implement an idea in hardware and build confidence in using instruments such as multimeters. They experience how motors stall under too much start-up load, notice they get hot, and hear them whine in the context of trying to perform a real task for which the product was designed. Design projects include an automatic seatbelt controller, a load hauling system, a power supply, a pedal-powered bike light. Dissection projects include cordless drills and bathroom scales.

The premise embodied in the course titled 'Exploring Engineering Intuition' is that there is no mysticism to engineering intuition. Intuition is developed by careful and systematic reflection on experience with hardware and through active integration and contextualization of theoretical knowledge. The Latin origin, *intuitio*—the act of contemplating—suggests that the ready insight gained without evident rational thought that we call intuition comes from careful contemplation. There is no formal textbook, but students are encouraged to read such books as *The Way Things Work* [17], *How Things Work in Your Home—and what to do when they don't* [18], *What Engineers Know and How They Know It* [19], and *Educating the Reflective Practitioner* [20].

The course's content-specific objectives are to build confidence with electro-mechanical hardware and to develop a feel for fundamental concepts (e.g., torque, how forces are distributed throughout a structure). The course emphasizes Table 1 qualities of:

- communicate (1);
- work as a team (2);
- self-evaluation and reflection (3);
- generate and consider alternative solutions (13);
- use a systematic approach to problem solving (14).

Particular effort is made to develop a questioning culture in the classroom by legitimizing basic questions such as 'what exactly is ground?' The springboards for these discussions are videotapes showing small student groups learning engineering concepts. This pedagogy is sometimes referred to as 'inquiry-based learning' [3].

Another example of a team-content centric course is a freshman-level laboratory course called 'The Introductory Engineering Test, Design and Simulation Laboratory' [21] created at Drexel University as part of the NSF-sponsored E4 program *Enhanced Educational Experience for Engineers.* While strictly speaking not a design course, the course does have attributes that foster the growth of several of the qualities listed in Table 1 in particular, qualities:

- communicate (1);
- work as a team (2);
- utilize graphical and visual representation and thinking (4);
- build-up real hardware to prototype ideas (15);
- trouble-shoot and test hardware (16).

The intense engineering laboratory experience at the freshman level is uncommon. The course is based on the ideas that experimentation is a critical and distinguishing element of the profession, experimental skills require time to develop, and entering students are interested in laboratory work.

In one hour of lecture and three hours of hands-on laboratory per week the course aims to:

- familiarize students with methods by which data are acquired, processed, and analyzed at an introductory level;
- acquaint students with basic experimental techniques, devices, and methods used in a broad variety of engineering disciplines;
- provide students with opportunities to learn how experimentation is used in engineering applications (e.g., validating estimates, assumptions or models; assessing properties of materials; determining the quality of products and processes; determining conformance of products to specifications; and analyzing design systems);
- acquaint students with basic principles, concepts and methodologies (e.g., presence of error, need for calibration, use of standards, accuracy, precision, reproducibility and sensitivity, analysis and interpretation of data, reporting of observations and conclusions).

C: Individual-process centric

Diametrically opposed to the team-content centric courses discussed above are courses that motivate process issues primarily through individual homework and projects. One freshman-level course has been identified in which much of the project-based learning is done via individual projects/assignments. The course is 'Visual Thinking,' a freshman-level engineering course created at Stanford University in the 1960's. The course is based upon a text by McKim [22]. This course serves as the introduction to the core problem-solving strategies and philosophies needed for successful engineering design. Its overall goal is to radically improve the student's fluency and flexibility in the generation of ideas, design concepts and problem solution candidates. The course gives students first-hand experiences in visual, kinesthetic and inner imagery, and helps them to understand the relationship between perception and creative problem solving by developing the interrelated skills of seeing and freehand drawing. Finally, it introduces the importance of human need as the inspiration and motivation for design. A graduate version of the course was created in the late 1980's. Drawing strategies are introduced (e.g., proportions, contour drawing, perspective), as are strategies for generating creative ideas (e.g., brainstorming, lists and meta-lists, synectics), and various issues pertaining to the practice of creative design (e.g., the nature of invention, express/test cycle; ideation logbooks).

The course involves three projects, one of which is a two-week design project done in teams of five (in which each individual has a well-defined part of the total design), a three-week project done in teams of two, and finally a three-week individual project on need finding. The first two projects involve rapid prototyping using Bristol Board, Foam-core, and other materials. In contrast to the three projects used in the Design Graphics courses at Iowa State and Hampton Universities, the first two projects in the Visual Thinking course often have a whimsical nature to them. They are always defined so as to have multiple solutions, and to be within reach of being accomplished by the vast majority of students in the class (which helps students develop greater confidence in professional accomplishment by successfully designing and fabricating a hardware project . McNeill *et al.* comments that, 'students must succeed to progress' [23]). Having three design projects allows the students to iterate on the design process itself.

The Visual Thinking course directly addresses qualities of:

- communicate (1);
- work effectively in a team (2);
- utilize graphical and visual representations and thinking (4);
- exercise creative and intuitive instincts (5);
- build up real hardware to prototype ideas (15);
- trouble-shoot and test hardware (16).

D: Team-process centric

A number of freshman-level courses have been created over the last five to 10 years that have a process orientation and utilize team-based learning. We will discuss two complimentary ways of introducing students to many of the design qualities listed in Table 1. The first of these has students study the artifacts and design processes of others, while the second has students engaged in doing design. (Of course it is entirely possible to combine these two approaches in a single course, and one example of this will be given later in this section).

First consider the study of the artifacts and processes practiced by others. Broadly labeled, this is 'case-based learning' and is nothing novel (even in design education). For example, ASEE sponsored the development of a series of design-based case studies in the 1970's. One recent twist to case-based learning has been to have the basis of the case study be the hardware itself. For example, Sheppard initiated a course in the fall of 1990 for freshman- and sophomore-level undergraduate engineering students called 'Mechanical Dissection' with NSF Synthesis Coalition sponsorship [7, 12]. The course was created to help students become familiar with the machines/mechanisms that surround them in order to help them gain confidence in their ability to work with, build up and manipulate them. It is built around a series of mechanical dissection exercises (here, 'dissection' refers to disassembling and reassembling a mechanical artifact). Students participate, both individually and in groups, in these in-depth dissection exercises so that 'experience (may be) the mother of knowledge' (after Cervantes). Examples of devices studied in the class include bicycles, electric drills, wind-up toys, sewing machines, engines, and computer printers. An important aspect of each of the exercises is for the students to become users of the device, identifying all aspects of the external functionality. Tasks related to these exercises include recording form and function of the device in a personal log book, mapping external-to-internal functionality, answering specific questions related to assembly or maintenance of the device, and participating in formal and informal presentations. More recently Regan and Sheppard [24] have been exploring the role of multimedia in enhancing the hands-on dissection experience. Other courses with a similar flavor have been initiated over the last few years. For example, at North Carolina State [25], the Product and Process Engineering Laboratory course uses product dissection while having students play the roles of user, assembler and engineer, in series.

Another approach to creating a 'team-process' centric course is to develop a course principally centered around one or several multi-week design projects. This has been done at: ESCEL Coalition (University of Maryland [26–29]); Foundation Coalition (Arizona State University [23, 30, 31]); Gateway Coalition (Ohio State [32, 33]); Synthesis Coalition (UC-Berkeley [34]); Harvey Mudd College [35], University of Colorado [36, 37], and the University of Wisconsin [38, 39]. This multi-week project approach, where students are engaged in hands-on experiential learning ('processes are best learned while doing' [23]), has been selected by these schools for two reasons: the project is so large that the members of a team must work together to complete the task, and large projects present engineering challenges that small projects do not. The courses are dominated by the multi-week project because it is the overwhelming theme that motivates both the fixed and flexible content covered during the term. Examples of projects include a robot arm for dispensing dog food, a chalkboard eraser for the handicapped, playground swing sets and see-saws, and solar desalination stills .

Some of the classes (for example, Ohio State and the University of Colorado) complement the multi-week project with 'mini' experiences, labs and/or projects that assist student learning the support skills and knowledge that they need to accomplish the design project (but the goal in learning these support skills and knowledge is not mastery, but rather literacy).

Besides being centered around a multi-week project, the approaches taken by all of the courses that were considered include utilizing coaching and having a competitive element to them. All use 'home-grown' course notes. Several (e.g., Harvey Mudd College) use a text as well (e.g., [17, 40]).

These courses take a holistic approach to design education, by having students experience that design is more than a project, more than teamwork, more than an oral presentation, more than analysis, more than creativity—it is a professional endeavor that is instilled in the future engineer via the curriculum. This experiential learning (referred to by Dym as 'traditional design education' [35]) is complemented in many instances (e.g., at Harvey Mudd College and at Arizona State) by providing students 'with a platform of design as a cognitive process so as to emphasize design as discipline, with its own structure, methods and vocabulary for both process and designed objects' (or in the words of McNeill *et al.* [23], 'to teach design, a clearly delineated process must exist.'). Dym refers to this as 'modern design education'.

These multi-week design project freshman-level courses aim to provide students with:

1. *An understanding of the profession:* a major objective of these courses is to have students discover engineering by doing engineering design. The courses also provide students with a hands-on introduction to professional practices, and laboratory and shop skills. Students should understand how engineers do their work and get a sense of where engineering fits into society as a whole (and whether it is for them). They are encouraged to ask their instructor to explain where in the curriculum they will gain the expertise to make such a decision with more confidence. In addition, the course should provide a context for future courses. The technical content required to analyze the design of the product is taught 'just in time.' This general goal of 'understanding the profession' supports Table 1 qualities: (6) find information and using a variety of resources (i.e., resourcefulness); to a lesser extent (7) stay abreast of professional practice; (12) define and formulate open-ended and/or under-defined problems, including specification.
2. *A creative learning environment and positive attitude:* these courses aim to establish a personal and friendly professional atmosphere conducive to developing the individual's creativity (and appreciation of the need to a balanced-brain approach to problem solving), a nurturing learning environment that fosters trust and support, and a positive attitude towards personal responsibility in lifelong learning (including study habits and self-discipline). This is particularly evident in the approach taken by Wujek [34]. All of the courses considered are built around the idea that project management and reporting can be taught, and that creativity can be fostered and nurtured. This general goal directly addresses qualities of: (5) exercise creative and intuitive instincts; (12) define and formulate open-ended and/or under-defined problems; (13) generate and consider alternative solutions.
3. *Skills for team-based problem solving:* all of the multi-week project courses aim to develop the spirit of teamwork, while maintaining respect for the individuality and diversity of students' cultural backgrounds. They aim to build a student's confidence as a contributor of ideas

and a member of a team. This general goal directly addresses qualities: (2) work on team-based skills; (13) generate and consider alternative solutions.

4. An appreciation for the fact that engineers are communicators. For example, students should learn to recognize the benefits of graphics and computer-based expression of concepts, and become more confident in their written and oral presentation skills. This general goal directly addresses qualities: (1) communicate; (4) utilize graphical and visual representations and thinking.

The reader should not get the impression that all of these courses, with their multi-week project focus and similar intents, are carbon-copies of one another. There are, in fact, major variances in the courses. Consider the following facets of the courses:

- where the projects come from;
- the product of the project;
- all groups working on the same or different projects?
- who are the coaches and mentors?
- the extent to which design methodologies are formally taught to students;
- feedback to students (use of exams, quizzes, etc.).

Each of these will now be discussed in turn.

Where the projects come from.

All of the courses using multi-week projects agree that projects must be selected with great care, should be open-ended and require integration of subject matter (i.e. synthesis), must provide opportunity for self-education and teamwork, and be credible and authentic to students (see Pavelich *et al.* [41] for an expanded discussion). Harvey Mudd College, and the Universities of Colorado and Wisconsin add that 'timely, real-life projects with clients work best' and all three work with public service and not-for-profit organizations (e.g., school for orthopedically disabled, rehabilitation hospitals, a regular hospital, the college, a church-led development organization in Nicaragua). Dym [35] notes that when working on projects from clients, the client must be genuinely interested in finding a solution. This is in contrast to UC-Berkeley, where students generate their own project definition [34], and University of Maryland, where teams are working on the same project definition generated by the teaching staff. Examples of projects at the University of Maryland include playground swing sets, see-saws, solar desalination stills and porch gliders. McNeill *et al.* [23] from Arizona State add that projects should be solvable using class methods, analytical models should be available to establish values of a few of the actual items in the design, graphic models should be used to set values, and that there should be an apparent tie between graphic and analytical models.

The product of project.

All of the multi-week project courses require final team reports and presentations. Some final reports must include fabrication specifications that would 'allow some person(s), unknown and unconnected to the design team or the course, to actually build the designed artifact.' What differs among the courses is the role that physical prototyping plays in the design process, and whether the final solution is reduced to hardware. At the University of Maryland, each team is required to build a functional prototype, and the actual fabrication process and testing are key parts of the course (taking up 40% of the semester). This is in contrast to Harvey Mudd College, where detailed design fabrication documentation is emphasized.

All groups working on same or different projects?

Both approaches certainly have advantages (and disadvantages); for example, if all students are working on the same project, the teaching staff can 'gear up' for a single technically sound engineering test of a single product—doing that for two or three projects in a semester would be too much. Having a standard test serves to validate that the product realization process is substantial (per Dally at University of Maryland where there is a single problem). It is also good for multiple solutions to the same design problem be developed. In addition, there is much tighter control over ensuring that supporting lectures and materials are relevant to the project at hand. One major disadvantage of the single project approach is that there is not likely to be a client, an individual who really wants a problem solved and who interacts with each group on a fairly regular basis (the course at Harvey Mudd is an exception to this). Another disadvantage is that students see only one project theme, which may lead them to have a narrow view of engineering design if the teaching staff does not make it a point to give examples in lectures of designs that are from different domains. The University of Wisconsin course is a hybrid of sorts. Each team of four students prepares a preliminary design for the problem that they are attacking, and makes a presentation to the other teams in the laboratory. One problem is then selected by group consensus, and the entire laboratory section prepares a final design, and actual device or a mock-up, and a final presentation for the entire class and their specific customers.

Who are the coaches and mentors?

In their paper, Teslow, Carlson and Miller [42], discuss Cognitive Apprenticeship as part of a constructivism learning environment. Apprenticeship involves observation, coaching, and mentoring, and includes taking pains to sequence instruction from simple to complex, increasing the global to specific skills. All of the multi-week project courses offer coaching to the freshman design teams. What differs between them is who the coaches are. At UC-Berkeley, the coaches are upperclassmen who are taking a sister and concurrent design course—they work as project managers. At the University of Maryland, the coaches are upper-classmen who apply for special status of fellows, and graduate student teaching assistants. Harvey Mudd distributes the coaching duties to a number of faculty members (so that no faculty member is coaching more than four teams, and each faculty coach gets course teaching credit), relies on the project liaison (who serves to represent the client-sponsor and acts as the primary channel of communication between each design team and the sponsoring agency), and on design jurors at the final presentation. The University of Colorado uses a teaching team (which includes two faculty members co-teaching the course, and several upper classmen TAs), as does the University of Wisconsin course. At Ohio State faculty, staff, graduate and undergraduate students serve as mentors.

The extent to which design methodologies are formally taught to students.

While all of the courses reviewed do talk about design methodologies to some extent, in some cases this discussion is much more extensive. For example, at Harvey Mudd College, students engage in a number of exercises that have them explicitly consider a variety of design methods/strategies. In addition, Harvey Mudd's course relies heavily on exposing students to design case studies.

Feedback to students (use of exams, quizzes, etc.).

Mechanisms for feedback range from weekly meetings with faculty advisors, review of draft proposals, exams and quizzes, and peer evaluation. At the University of Wisconsin, each student sends a weekly e-mail report to the teaching staff, and receives personal feedback in reply. Students keep a journal in which they record all that happens in class and laboratory, and answer questions that are designed to help them reflect on their experiences and learning. The teaching staff reads these student journals and provides feedback on the quality of the records, writing, personal reflections, etc. At Ohio State, the students present their project progress in weekly oral presentations to the faculty/staff team. They have to show their notebooks and design components have to be demonstrated. The students keep weekly journals for their entire freshman year, which are submitted to a file server where the student information is stripped and sent to a separate file, and what the students write is sent to the faculty staff team.

It is important to note that assessment data that are out there (scant as they may be) on the effectiveness of the multi-week project approach at the freshman level show positive results. For example, McNeill *et al.* [23] show that students' perception of their profession improved significantly as a result of the multi-week project class experience. In addition, when asked to respond to the statement, 'I liked the freedom of the open-endedness of the project,' 73 percent marked a 1 or 2 on a scale of 1 (strongly agree) to 5 (strongly disagree). It was also found that introducing a design component at the freshman level had an impact on students' attitude toward open-ended projects in higher-level courses. Student acceptance and performance on these projects improved each semester and could be correlated directly with whether the students had the prior, freshman-level design experience. Preliminary data from the University of Maryland shows an increase in retention rate of 2.5% (one-year-later retention data) following the adoption of their freshman design course (ENES 100), and faculty comments such as 'I've never seen students so motivated to take statics in 30 years [since the start of ENES 100].' Findings are similar at Ohio State University where results show that more of the students in the new program are being retained in engineering and are doing better in subsequent engineering, physics, and mathematics courses. From student journals, interviews, and meetings it is obvious that the students feel part of the College of Engineering and that they know engineering faculty.

IMPLICATIONS OF THESE APPROACHES

We have reviewed a framework for categorizing freshman activities that supports the development of many of design qualities listed in Table 1 (this framework is further discussed in a companion paper [1]). We then presented examples of courses in each of these four quadrants that are being taught in support of engineering programs across the US and how these courses relate to the qualities. Many of these courses are a direct product of NSF sponsorship. All of the courses, from Calculus to term-long design project courses use open-ended problem solving as a vehicle to create experiences that allow students to develop these qualities. They differ in the extent that the Table 1 qualities are major, explicit course objectives, and to the extent that student activities are individual- or team-based. There is also variability as to whether the course is major specific (e.g. only for civil engineering majors as in the course presented in [43]) or for general engineering majors (e.g. Calculus, Strength of Materials, the design course at University of Maryland).

Integrating design concepts and open-ended problem solving into the freshman year introduces teaching and learning challenges for all of the courses that have been discussed. Some of these challenges are:

- re-evaluating the role of the instructor;
- re-evaluating the role of students;
- providing students with meaningful (and 'doable') open-ended problems;
- assessing student performance;
- rescoping expectations of future instructors

and how the freshman year meshes with sophomore activities.

We will address each of these challenges.

Re-evaluating the role of the instructor.

When students are working on open-ended problems that have multiple valid solutions, the instructor ceases to be the sole expert who knows the right answer. He or she may need to act more as a coach or mentor to students as they work through the process of problem solving. This change in position may be foreign and uncomfortable for instructors. As part of this coaching/mentoring role, the instructor needs to know when not to interfere, resist the urge to over-teach, and expect that things do not always go as planned (from Pavelich *et al.* [41]). The instructor needs to be 'reactive,' responding to the technical needs that arise as the project unfolds. An additional challenge, particularly with freshman, is presenting content material (e.g. types of bearings, power considerations, gear trains) in a timely, connected manner amid the hands-on exercises that students are engaged with.

One way to assist faculty in learning new teaching methods is through faculty workshops and materials which 'train' them for teaching design at the freshman level (as is done at the University of Maryland, and with the Harvard Calculus workshops). Other workshops such as 'Integration of Creativity into the Mechanical Engineering Curriculum Workshop' (put on by Professors Faste, Roth and Wilde at Stanford University) and the 'Integrating Design into the Curriculum Workshop' (put on by Engineering Design Services, Dallas, TX) are offered annually to aid faculty in developing appropriate teaching methods for design education. Faculty need to use sound pedagogical techniques, present appropriate content, and instill appropriate values at this 'tender age' of the engineering students. Another approach is to have faculty mentor one another (really using the apprenticeship ideas espoused by Constructivism), by, for example, having them co-teach with other faculty who have previously taught project-based design classes. Many of these comments also apply to course teaching assistants and coaches; they may need pointers on how best to assist student growth.

Re-evaluating the role of students.

It is likely that the high school experiences of most college freshman lacked significant open-ended problem solving and team work. In fact, high school environments may be down right competitive. Students need to learn how to work in a team (which includes learning how to trust their team mates and share information). In addition, they need to learn to view the instructor as a mentor, not as an authority figure. Finally, students need help in setting goals, learning to deal with the frustration of teamwork, and the uncertainty and ambiguity of open-end problem solving. Team-based exercises are often useful in this regard (e.g., [44]).

Faculty can assist students in this by making course expectations and objectives as clear as possible, using upper classmen coaches or panels, showing samples of work from years past (which is done particularly well at Santa Clara University [14]), doing mid-quarter assessments and or 'minute papers' [45], distributing raise sheets (students anonymously distribute raises between themselves and their team mates, justifying the dollar allocations—a good reflection exercise that also gives the instructor a better sense of team member contributions), and by encouraging open forum student discussions.

Providing students with meaningful (and doable) open-ended problems.

Most of the courses that have been discussed in this paper consider real-world design problems, which some believe not only aids in the learning process, but also 'jump starts' the student-to-professional transition [46]. Two exceptions are in the Visual Thinking class at Stanford and the Rube Goldberg project in one section of the freshman course at University of Colorado (both of which are very popular with students). Whether a 'whimsical and fun' project, or a real-world project, projects should be such that, if possible, prototypes can be built or simulated with CAD systems on high-end personal computers or workstations. In addition, there must be balance between the openness of the project (e.g., many possible solutions) and students actually being able to succeed. Project selection remains a critical component of creating meaningful freshman experiences.

Assessing student performance.

It is much more difficult to grade student work when there are multiple 'right answers', students may be working on different design problems, and where the path of how the student got to his or her final solution is as important as the final solution. This difficulty is compounded if the work is team-based.

Faculty need to explore alternative assessment techniques in reviewing student work that has a design element to it. For example, design reviews (especially with outside panels) are a good model, as are portfolios and journals. Students can particulate in self-assessment, which is consistent with quality (3), Table 1. These are examples of authentic assessment techniques. In [47], Moore offers some sound advice on grading design courses.

Rescoping expectations of future instructors and how the freshman year meshes with sophomore activities.

After a freshman year rich with open-ended problem solving, the sophomore year may seem 'the valley of despair' (expression attributed to Dr. Jackie Sullivan at the University of

Colorado-Boulder). Sophomores may be thrown for a loop when they find all of their sophomore-level courses to be traditional in that they are asked to engage in very little open-ended problem solving and most homework assignments are individually based. This state of affairs indicates that the sophomore-level engineering-related activities need to be reviewed and revised, too. A number of approaches may be taken, some requiring modification of existing courses. For example, at the University of Maryland small design projects have been incorporated on a pilot basis in Statics and in Mechanics of Materials. In Statics student teams design, build and test a model bridge, and in an honors section of Mechanics of Materials, student teams design and build diffused light polariscopes with structural models. Laura Demsetz (UC-Berkeley) as part of the Synthesis Coalition [48] has developed a series of open-ended design problems that she integrates into her Statics teaching. She sees these problems as a way to help students gain confidence in design/synthesis and develop engineering judgment early in the engineering program. Students rely on whatever resources are available—experience, engineering judgment, reference material in the library, reference material provided by instructors—to find the information required to solve the problems. There are many parallels between Demsetz's work and that of Bucciarelli.

In addition, sophomore-level instructors must be made aware of new skills that students bring with them (such as spreadsheet skills, team work skills, and CAD and sketching skills) in order to leverage and utilize them.

Another approach is to create new sophomore-level courses that have 'design process' as a major theme. For example, both the University of Maryland and Stanford University have created product realization experiences for sophomore-level students. At Maryland the sophomore course builds on the first design course, but considers as a case study a real product that is mass produced by a local company competing in the global market. This course introduces engineering students to some of the business aspects of the product realization process, provides a complete study of the method for developing a product specification for a real product, and introduces a sense of mass production.

At Stanford University the course 'Manufacturing and Design' emphasizes prototype development techniques as an intrinsic part of the design process. The goal of the course is to graduate students who understand the relationships between design and manufacturing conceptually and through experience. Students learn how to make decisions based on multiple sources of incomplete information, and learn something of the complete spectrum of manufacturing processes from milling to scanning tunneling microscopy. Fundamentals of machining, welding and casting introduced in lecture are supported by lab exercises and field trips. The interplay of design and manufacturing is experienced by students as they engage in an individual term project chosen, designed and fabricated by each student (but small groups work together with a common coach).

A third approach has been taken at Aalborg University [49], the Colorado School of Mines (Pavelich *et al.* [41]), and at Clemson and West Virginia Universities (as part of the SUCCEED Coalition [50]). These schools have created integrated, multi-course sequences that have as explicit goals:

(1) open-ended, team-based and problem solving;
(2) oral, written and graphical communications.

Aalborg uses project-organized studies throughout the four year undergraduate experience, and has been doing so for the last 20 years. The program at Colorado School of Mines (called Engineering Practices Introductory Course Sequence, EPICS) is comprised of four courses that extend over the freshman and sophomore years. At Clemson and West Virginia students work on the same case study from different perspectives in five courses spanning the sophomore to the senior years (e.g. designing and understanding a process for separating ethanol from water in a distillation column).

CONCLUDING REMARKS

At this point the reader may be wondering which of the approaches to introducing design and design qualities at the freshman level is best for his or her institution. For example, is it better to introduce these qualities by creating one freshman-level design class, or to work in shifting the positions of calculus, strength of materials, and freshman graphics? Or is it better to look at integrating more broadly calculus, physics and introduction to design at the freshman level. For example, the Ohio State and Arizona State University multi-week project courses discussed above are part of an integrated freshman year. These design courses are explicitly integrated with freshman-level mathematics and engineering mechanics courses. It is particularly noteworthy that there was a session at the 1995 Frontiers in Engineering Conference devoted to this very topic and where Refs. [31, 51–53] were presented.

To answer the sorts of questions posed above, a school needs to look at its faculty, student body, facilities, and industrial partners, as well as the third dimension of the framework presented in Fig. 1—this third dimension is time. Ideally a student's four years in an engineering program would contain design experiences in each of the quadrants in Figure 1 and in total touch on all of the qualities in Table 1. To quote from ASME *Guidelines for Mechanical Engineering Evaluators*, 'An engineering design curriculum is more than a collection of separate and independent courses. It is a combination of interrelated courses which are carefully integrated to develop student abilities and knowledge throughout the program. The interrelationships are not always obvious to students, so they must often be pointed out. Nor do separate courses effectively build one on the other without faculty effort directed toward that end. The progression of courses from the elementary to the more advanced (the time dimension), with the more advanced courses making effective use of the earlier course material, should be shown in the curriculum, in courses syllabi, and in the conduct of courses.' This means that faculty collectively need to design and implement (and redesign, as necessary) a curriculum that has multiple experiences and approaches to teaching design.

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