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Cumulative Knowledge and the Teaching of Engineering Design Processes

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1. Introduction

The engineering design process, whether implicitly or explicitly employed, is central to the practice of engineering. Because of this, and because of pressures from the economy and ABET, engineering programs have made an increasing commitment to teaching design and the question "What is design?" is being addressed more and more successfully. One can now see a partial consensus around a new set of ideas that are closely related to the process of product design and development employed by industry. This allows us to employ a pedagogical construct that is standard in other areas of the engineering curriculum: cumulative knowledge. Our students follow curricular paths that are full of necessary prerequisites, but generally not with respect to the design curriculum. We need to identify a cumulative learning process in design from the first course to the first job.

The ABET definition of engineering design is "the process of devising a system, component, or process to meet desired needs."[1] The design-related requirements that ABET places on U.S. engineering programs for accreditation state that a curriculum must include most of the following features:

- development of student creativity;
- use of open-ended problems;
- development and use of modern design theory and methodology;
- formulation of design problem statements and specifications;
- consideration of alternative solutions;
- feasibility considerations;
- production processes;
- concurrent engineering design; and
- detailed system descriptions.

When providing design projects, ABET also indicates that the design experience should:

- include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact;

- be 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;
- be taught in section sizes that are small enough to allow interaction between teacher and student;
- be an experience that must grow with the student's development; and
- focus the student's attention on professional practice and be drawn from past course work.

There exist various models of the design process, but all have certain features in common. All design efforts involve systematic problem solving, they are cyclical and iterative, and they have a start and a finish. ABET states that "among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation." Cross[2] summarizes many different design process models available in the literature. To provide a reference point, we posit that the engineering design process may be thought of as having roughly four phases, although it is important to note that the design process is iterative, and often the engineer must return to a previous phase:

- defining the problem;
- developing concepts or solutions;
- evaluating, and choosing among, solutions; and
- implementing and communicating the design.

2. Accumulating and Articulating Design Knowledge in the Curriculum

Design has been strengthened in the engineering curriculum over the last decade. Its main functions in the curriculum are the motivation and retention of students in lower division courses, as well as the use of capstone design courses to show students applications of engineering knowledge and to prepare them for the applied and collaborative workplace most will enter on graduation. Pressure from ABET, government agencies, and industry has driven this renewal of interest in design.

We are interested in taking design to the next level where it has the cumulative-knowledge status of other disciplines and capstone courses can be taught based on expectations—and possibly prerequisites—of knowledge of design already attained by the students taking the course. Thus, design courses should be based on cumulative knowledge and articulated with expectations and prerequisites. It is also the case that two design courses bracketing their studies are not enough to adequately treat the subject and, ideally, students should be taking a design course each year.

We have come to this position based not only on the development of design knowledge over the last 5–15 years but also on the degree of consensus that has emerged over the same time frame. This is the first such consensus and, not surprisingly, it has taken place around a trans-disciplinary approach to design. Heretofore, design was largely idiosyncratic with each exponent providing his or her views. The main exception, Pahl and Beitz[3], is rather abstract and perhaps difficult to use in the classroom (although the second edition is much better than the first in this regard). Cross[2] has produced texts that are much easier to use in the classroom. The new view, focused on the best industrial practices, is well represented by Ulrich and Eppinger[4] and Otto and

Wood[5]. Some other texts, which follow the new paradigm in varying degrees, include Dieter[6] and Pugh.[7] Pahl and Beitz, and, later, Cross, were early pioneers in the 1980s of a trans-disciplinary approach to design. Ulrich and Eppinger were very effective in reaching audiences in the United States with the first edition of their book in 1995.

The new consensus in design is paying more attention to problem development and customers needs, project management and the development process leading to and including aspects of manufacturing, concept generation, objectives trees, and selection processes; technology assessment (tradeoffs), including social and environmental life cycle assessment; prototype development and testing; designing for manufacturing and industrial design; and production economics. There is also an implicit assumption about skill development in such areas as CAD and graphics, tolerances, and generating and analyzing data. There has been a tendency to reduce design to (consumer) product design that will need corrective action at some point to include services, systems, and the public sector, among other topics of design.

The context of engineering design and development is becoming global in nature and, now, engineering students can expect to work in multi-cultural teams for multinational organizations in overseas locations. They will work and live in milieus that have different technical norms, standards, and procedures, and different cultures and languages than those of their native country. Engineers in the global economy also work increasingly in virtual teams held together by contemporary information technology since they are in different industrial units and perhaps in different countries.

The process of economic and cultural globalization has continued to the point where it now must be a focal point for training engineers for the future. Students need to be aware of the changing nature and scope of the global economy; emerging patterns of corporate structure in the global economy including the use of the 24-hour world clock in performing design and manufacturing tasks in all time zones; the regulatory environment and the intersection between national and international practices and standards in engineering; global technological diversity; new environmental methodologies such as life cycle assessment; cultural and language differences; the role of cultural and national diversity in product design and development; and cross cultural issues in the management of technology in the global economy.

Other issues that need to be addressed, but which fall outside the new approach to design, are those covered by some of the ABET requirements concerning the ethical, social, environmental, and business environments of the global economy. For example, ABET requires that to be accredited, schools of engineering must provide engineering students with "the broad education necessary to understand the impact of engineering solutions in a global and societal context." (ABET 2000, 3(h)).[1] Students should study the corporate and stakeholder environments of product design and development; social and environmental impact; and diversity in approaches to users, customers and markets.

3. Engineering Design in the Curriculum

Presently, many engineering programs have two courses containing the primary engineering design content, these being a first or sophomore year introductory engineering design course and a senior capstone design class. This is the case at Penn State, and a recent review article of design programs[8] described similar situations at MIT, University of Texas, and the U.S. Air Force Academy. In most programs, however, the capstone design class is not based on assumptions about the level of knowledge of the design process that incoming students have. Design currently does not have the cumulative-knowledge status of other disciplines; hence, capstone courses cannot be taught based on design knowledge prerequisites. Thus, design courses throughout the curriculum should be based on cumulative knowledge and articulated with expectations and prerequisites.

We understand that a few large institutions like Stanford University have design degree programs and a few others, like Worcester Polytechnic, are small enough to have considerable flexibility in adapting their curriculum to design needs—if they are also creative enough to do that. In this article, we are searching for a path ahead for the vast majority of engineering schools that do not have departmental or institutional level commitments nor are likely to get them. A quick web search of "design across the curriculum" finds largely discipline-based, and not cross-disciplinary, approaches. The new approach to design stressing cross-disciplinary methods provides a basis for expansion and for a new cumulative-knowledge approach to the design curriculum even in large engineering schools that are still largely based on the old discipline-based design plus a motivational introductory course.

How broad-based the new approach is, may be open to some debate and something we will address in a future article. It is particularly focused on mechanical and industrial engineering, two fields that are so close that they are often merged in Europe. For example, we know that faculty in Mechanical Engineering, Industrial Engineering, Electrical Engineering, Engineering Entrepreneurship, and the first-year design course at Penn State already use Ulrich & Eppinger. Faculty in Industrial Engineering at Arizona State University also use it, and the same approach, using Pahl and Beitz, is used in Mechanical Engineering at the University of Leeds in the UK. We believe the basic tenets of the approach have very broad applications in engineering and we hope to discuss this in the future. In this article we certainly assume that this new approach has broken the mold of discipline-based design—which will still continue, of course.

The First-Year Engineering Design Curriculum

The typical sequence employed by faculty teaching ED&G100: *Introduction to Engineering Design* at Penn State is a half-semester structured design module followed by a less structured, but more in-depth, industry-sponsored design experience. Some faculty also complete one or more very short, 1–2 week focused design projects in addition to these two. It is not possible to present all of the principles of the engineering design process—topics such as user needs analysis, concept generation, concept selection, etc.—before beginning the first design project. Hence, the students begin their first design without an awareness of the process they are employing. As the semester progresses, these topics are presented and explicitly employed in the second design project. The honors section of ED&G100 has been using information technology to facilitate cross-national teams for the last five years. Many of their industry problems come from industries in France developed by colleagues at a French university.

The second project is used to create a realistic engineering design environment for students via an industry-sponsored design project.[9] Every semester a different industry sponsor is recruited to present a design problem and determine deliverables. In general, these design projects are open-ended in nature and do not come with step-by-step instructions. This project provides a fertile environment for introducing the many elements of engineering design, and because students find themselves needing the requisite tools to do well with the project, the design topics are quickly assimilated.

One of the changes we have recently made to the course is the development of a custom book[10] that presents the topics we feel the students should learn in the introductory course. The previous materials were largely graphics based—representing the historical evolution of the course—whereas the new book provides material for all aspects of the course: design, graphics, and CAD. As a way to tie together this introductory design course and capstone courses, the design materials (without the graphics and spreadsheet chapters) have been provided in another custom book[11] and recently adopted for the electrical engineering senior capstone course as a method for reviewing engineering design previously learned 2–3 years earlier. The important thing to note is that this is a first step at requiring some design exposure, if not quite prerequisites, for the capstone design course.

The Senior Capstone Design Course

As part of the capstone design curriculum, "industry-sponsored" and "professor-driven" design projects are now fairly commonplace. Many engineering programs (including Penn State's) provide capstone design experiences via industry-sponsored design projects.[12] These projects are excellent methods for providing meaningful "real world" design experiences, although they have their own set of difficulties. Professor-driven projects in the capstone design course are also valuable in that the design experience can be tailored to course content and desired educational outcomes.[13] Reverse engineering techniques in teaching design have also been employed with success in capstone and introductory design classes.[16]

The "Missing" Middle Years

Having a first-year or introductory design experience and then a capstone senior course in design raises several obvious issues. We may establish competencies that are learned in the first year design course as desirable and known for entry into the senior course. However, as two or more years go by, retention of knowledge learned will not be high. (In fact, in the past when the entry-level engineering course was based largely on graphics, faculty teaching the capstone design courses often complained about the students poor knowledge and skills in graphics.) As a result, capstone design courses are often taught as standalone pre-professional courses that owe little if anything to the entry-level course. This is a result of lack of retention and no accumulation. Even if cumulative, two courses cannot cover all, or even enough, aspects of design anymore. Perhaps we do not need to require more courses of all students but all those entering a career of design should have far more than these two courses. To be fair, there are some other specialized courses in design as well as other courses that are very relevant to design. But in terms of a trans-disciplinary approach dealing with the advances of the last decade or so, there is very little in the middle years. Indeed, if even some students who were interested in design took one or two courses in the middle years, one can speculate that the availability of these courses would make a marked impact on the capstone courses and provide a natural cohort of team leaders.

One area in which an intermediate course would be of great value would be in product design and development. Preferably, such a course would be set in the global economy and also serve as preparation for what is an increasingly important source of the best jobs. Using information technology, it is very easy to form (but perhaps not necessarily operate) cross-national student teams and to use faculty in other countries to give lectures and lead discussions. We have actually done this in one course for the last five years and are planning expansion to multi-point teams. In this course, half of the industry design projects come from industries in France, and on one occasion we were able to have an A-V conference between the French and American students and a representative of the French industry. In doing this we can enhance the knowledge of the participating students of the global economy and of engineering practice in other national economies. We can also improve the ability of the students to work with people in other countries and with people from other cultures.

Under global product design and development, a wide array of topics may be covered including the corporate and stakeholder environments of product design and development; diversity in approaches to users, customers and markets; concept generation, trees, and selection processes; technology assessment (tradeoffs), including social and environmental life cycle assessment; prototype development and testing; designing for manufacturing and industrial design; production economics; and project management. National and international standards, design ethics, teamwork, conflict resolution, cross-cultural awareness, and human resource development should also be studied.

Another possibility for the middle years is “harnessing” the many student-initiated design projects,[14] which could benefit significantly by formalizing the relationship between the student project and the design education process. This might be accomplished through methods such as establishing a design course for the entire project or providing independent study opportunities and/or incorporating smaller pieces into established design courses.

Another important feature of student team projects is that they are generally vertically integrated, that is, they involve students at all stages of education, from first year to graduate student. This type of vertical integration, while occasionally attempted in established design courses (*e.g.,* see Clayton[15] and Tao[16]), is generally quite difficult to get to work in practice. Vertical integration provides several natural benefits, however. One of the benefits is that students learn from other students. The more advanced students often are the leaders and mentors of the younger students; as younger students advance, they subsequently take on the role of mentor to the “new recruits.” Hence, the more senior students obtain experience in realistic management situations and the younger students benefit form the mentoring as well as a preview of what is to come in academics and careers.[16] This is very similar to what the students will see in engineering practice as they move from subordinate to supervisor.

4. Articulation

It is important to develop a broad agreement among design faculty in *different* engineering majors so that what constitutes design knowledge and what parts of it should be learned in which courses is widely understood and agreed upon. It will then be much easier to establish course competencies, to incorporate prerequisites, and to advise and recognize the student initiated design projects. Providing an opportunity to get a minor in design will become easy once a few more courses are established and this might provide the organizing principle for accumulating and articulating design knowledge in the curriculum.

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