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Engineering Design: So Much to Learn*

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This paper recaptures remarks made at the opening of a workshop on learning and engineering design by the workshop's organizing committee's chair. Held at Harvey Mudd College in May 2005, and supported by Mudd's Center for Design Education, Mudd Design Workshop V brought together engineers and social scientists—in their roles as educators, researchers, and practitioners interested in learning and in design—to identify and articulate important issues about learning in engineering design. The remarks detailed below are intended to provide a context for the presentations and discussions that comprised the workshop by exploring some of the many difficulties attendant to teaching design. While this address may have been preaching to the choir, it is nonetheless somewhat unsettling to list the myriad of skills associated with good design. In addition, the point is made that while the difficulties of teaching design may still be underappreciated by the (much) larger analysis community, the benefits associated with teaching design are increasingly seen as the primary goals of engineering education—which suggests that in the long run, design and synthesis will at least draw equal to, if not prevail over analysis and reductionism as the prime movers in engineering education.

WHAT DOES IT MEAN TO DESIGN, TO LEARN, TO KNOW?

AS HAS BEEN DONE before (e.g., [1]), this fifth Mudd Design Workshop (MDW V) was designed to stretch the reach of prior workshops [2–4] to include both ideas and colleagues from other domains with an interest in learning—alongside those interested 'only' in engineering design—in its Organizing Committee, its presentations, and its audience. Now the phrase *engineering design* is one that takes on a wider variety of meanings depending on both context and interlocutor, as has been extensively detailed in [5], and from which work this paper derives much of its inspiration and content. In fact, the definition of design adopted in [5] articulated the idea that engineering design is a *thought* process that depends on the systematic, intelligent generation of design concepts, as well as of the specifications that make it possible to manufacture or realize these concepts.

Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.

This definition also recognizes that designers typically have a client (or customer) who, in turn, has in mind a set of users (or customers) for whose benefit the designed artifact is being developed. And while this formal definition stands design educators, researchers, and practitioners in good stead, it does not capture the flavor of views about design thinking that will be addressed in the next section.

The verb *learn* may also mean different things to different people, and even different things to the same person at different times or in different contexts. Rather than propose new definitions, this discussion begins with a review of the meaning of the verb *learn* as given in *Webster's New Collegiate Dictionary* [6]:

> learn (*vb*): to gain knowledge or understanding of or skill in by study, instruction, or experience

Note that this definition places essentially complete responsibility on the learner, as it is she or he who must *gain* the knowledge, whether by personal contemplation, being taught, or engaging in the very activity being learned. Since this definition also suggests a direct link from learning to knowing, it seems also useful to look up what it means to *know* [6]:

> know (*vb*): to perceive directly; have direct cognition of
> *syn*: know, believe, think, to hold something in one's mind as being true or being what's purported to be true

Clearly, *know* has several synonyms and there are likely endless debates one might have about whether *knowing* something is the same as *believing* something, and so on, and there are clearly domains whether such distinctions could really matter—for example, think of theology. Since the only aim here is to set a stage for the vigorous intellectual discussion of which this workshop will be comprised, the fine distinctions hinted at here are eschewed.

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Finally, perhaps as an act of self-defense, one further definition is listed, this one taken from an entirely different context [7]:

> *Synthesis*, by definition, leaves out, collapses, and generalizes.

Thus, if the author has erred in synthesizing the work of his colleagues [5], remember that he is only collapsing and generalizing!

THE SKILLS OF DESIGN THINKING

Sheppard [8] observed that engineers 'scope, generate, evaluate and realize ideas'—a characterization that emphasizes how engineers *think* and highlights how ideas are *created* (i.e., scope and generate), *assessed and selected* (i.e., evaluated), and *brought to life* (i.e., realized). It has also been noted that *analysis* cannot by itself adequately account for the mental processes that lead to successful *synthesis* or *design* [9]. Experience both in the real world and in the classroom tends to confirm this proposition, and few would disagree that analysis is easier to teach than design. Why is design—no doubt a fascinating and complex human endeavor—so hard to learn and so hard to teach?

The answer is (relatively) simple. As will be outlined immediately below, design thinking requires a broad spectrum of talents and approaches in which analysis may play an essential supporting role, but in which various kinds of judgment, reflection, and experience are far more essential to the design task at hand. On the other hand, most of the content taught in today's engineering curricula is associated with mathematics and the sciences, wherein students are required to learn and apply scientific principles to solve engineering problems, using *systematic questioning* to analyze constrained situations to reach verifiable (i.e., 'truthful') answers or solutions [10]. While systematic questioning describes *analysis* well, it does not apply straightforwardly in a *design* context, in spite of the fact that design educators already argue that the tools and techniques used to support designers are [11] ' . . . ways of asking questions, and presenting and viewing the answers to those questions as the design process unfolds'. And while accepted models of the design process (see, for example, Figure 2.4 of [11]) show iterative loops between various stages of design, it is a different kind of questioning that takes place during the design process [10].

Dym, et al. [5], argued extensively that good designers generally exhibit several attributes in their *design thinking*. Thus, designers:

- view design as *inquiry*, or as an iterative loop of divergent-convergent thinking, and thus are able to *tolerate (intellectual) ambiguity*;
- maintain awareness of the *big picture* because they are sensitive to system component interactions and to the design of systems;
- do not assume the world is fully deterministic, and so they are able to *accommodate uncertainty*;
- able to *make decisions*;
- are conversant with and can both *think and communicate in the several languages of design*;
- are able to view design as a social process and *can work successfully as members of design teams*.

A HANDLING AMBIGUITY

Any design project begins with questioning during the *problem definition* phase of the process [11]. Once a series of objectives for a designed artifact has been set out, the designers—both in 'real' and class design studios—work to know what the client really wants. What is a safe product? What does 'cheap' mean? What is the best . . . ? Questioning is clearly an integral part of design.

Aristotle [12] proposed that 'the kinds of questions we ask are as many as the kinds of things which we know.' In other words*, knowledge resides in the questions that can be asked and the answers that can be provided* [5]. The nature of systematic questioning in a design context has been studied and it does seem that designers' inquiry and thinking processes might have unique, identifiable characteristics [10].

A common premise of such discussions is that specific answers or sets of answers exist for given questions, a characteristic of *convergent thinking*, where the questioner attempts to converge on and reveal 'facts'. Answers to converging questions are expected to be verifiable, to hold *truth*-*value*. In design questions asked for which there are multiple alternative known answers, whether true or false, and multiple unknown possible answers. The questioner wants to expose alternative known answers and *generate* possible unknown answers. Such questions characterize *divergent thinking* which attempt to diverge from facts to the *possibilities* that might be created from them. Eris [10] identified such questions as *generative design questions*, noting that questioners may not be concerned with verifiability (i.e., truthfulness) of the potential answers.

The key distinction between the two classes is that *convergent questions operate in the knowledge domain*, whereas *divergent questions operate in the concept domain*. In this context, *design thinking is seen as a series of continuous transformations from the concept domain to the knowledge domain*. Such questioning and thinking also reflects the process by which designers add to the store of engineering knowledge [13].

Finally on this point, it might be noted that engineering curricula effectively convey Aristotelian convergent inquiry that promotes the *reductionist* reasoning associated with the engineering science model. In the design or *synthesis* model, divergent inquiry takes place in the concept domain—in which answers are not necessarily verifiable—which situation often seems to conflict with the values that are central to the predominantly deterministic, engineering science approach.

Maintaining a systems perspective

In recent decades engineering designers are making increasingly complex products and systems with evermore components and interdependencies [14] and with expanded design boundaries that include environmental and social impacts in their designed systems [15]. Engineers and designers thus need to cope with complexity, in response to which specialized programs for system design, systems engineering, and closely related areas have emerged [16]. The *system design* and *systems thinking* skills that good designers exhibit and which engineering students should experience include recognizing the systems context, reasoning about uncertainty, making estimates, and performing experiments—all of which might be thought of as desirable *habits of mind* for designers.

- *Understanding systems dynamics*: Good system designers anticipate unintended consequences that emerge from interactions among the multiple parts of a system. Unfortunately, this skill is not common and can be difficult to learn, as a result of which some have proposed a research agenda intended to enhance the scientific understanding of systems thinking and to better develop educational experiences that can efficiently improve reasoning about system dynamics [17].
- *Reasoning about uncertainty*: Designers frequently work with imperfect models, incomplete information, and sometimes with ambiguous objectives, the effects of which uncertainties are even more prominent in systems design. Some have argued that undergraduate engineering curricula do not sufficiently emphasize the roles of probability and statistics in engineering (e.g., [18]), and many studies in cognitive psychology have shown that people are prone to serious errors in probabilistic or statistical thinking, including neglecting prior probabilities, being insensitive to sample size, and not understanding regression [19]. Engineering educators have worked to overcome these difficulties by emphasizing conceptual understanding, using more hands-on teaching methods, and more graphics and simulations, but Wood argues persuasively that there is much further to go, and that uncertainty should be made central to design education [20].
- *Making estimates*: During systems design, the system often exceeds a designers' capability to grasp all of the details simultaneously because of a growing number of variables and interactions. One human strategy for keeping a system manageable is to limit the number of factors considered—and preferably the most important ones. Good designers are typically good at such estimation, that is, they can generally determine the relative magnitudes of various parameters and identify those that can safely be ignored (for certain situations). Sadly, engineering graduates are generally not good at estimation, perhaps because engineering education often emphasizes computer-based methods for precise calculation at the expense of modeling and approximation skills.
- *Conducting experiments*: In most cases, system design requires some use of empirical data and experimentation, in addition to applying fundamental scientific principles. This circumstance is driving a trend to teach engineers in their education and in industry about the *design of experiments*, so that they can plan experiments and properly analyze the results. However, the statistical methods of experiment design alone will not by themselves enable engineers to learn effectively through experimentation. In fact, Box and Liu [21] argue that overly rigid adherence to statistical measures of optimal design will have a deleterious effect on the learning process, and that engineers must also learn to alternate between inductive processes and deductive processes, using physical understanding or engineering models to inform the experimental approach and then updating their models and their understanding based on measured data.

Making design decisions

Several decision-centric design tools and frameworks have been developed in recent years [22–28], with a common underlying premise for these *decision-based design* frameworks that design is a rational process of choosing among design alternatives. In addition, some decision-centric views [23] use a deterministic, optimization-based model to account for ambiguity. Radford and Gero also argued that exploring the relationship between design decisions and the performance of the resulting solutions is fundamental to design, with goal-seeking introduced directly into design exploration through optimization [23]. Dieter showed the relevance to design of decision-centric by constructing a decision matrix to determine the intrinsic worth of outcomes associated with competing design concepts [24], using methodology that is similar to the widely used 'Pugh selection chart' methodology [25–28].

The role of decision making in design—and, particularly, the identification of design *as* decision making—has not been without critics [29]. However, it is hard to imagine a designer who is not focused on the outcome of design decisions being made [30]. In addition, decision-based approaches to design assume that designers only make critical decisions *after* design concepts and alternatives—different choices, with different outcomes—have been generated, and that generated alternatives can be represented in forms to which decision-based design can be applied. But decision-based design cannot suggest *how* concepts and alternatives are generated, which is often regarded as the most creative aspect of design thinking. Some decision theorists also acknowledge these limitations by recognizing that decision analysis can only be practiced after a certain point. Howard asked [31], 'Is decision analysis too narrow for the richness of the human decision?' He then argued that 'framing' and 'creating alternatives' should be addressed *before* decision analysis techniques are applied, observing also that 'Framing is the most difficult part of the decision analysis process; it seems to require an understanding that is uniquely human. Framing poses the greatest challenge to the automation of decision analysis.'

The languages of engineering design

Different languages are employed to represent engineering and design knowledge at different times, and the same knowledge is often cast into different forms or languages in order to serve different purposes. Design requires the use of several languages in addition to mathematics, as do many other types of human cognition. Design knowledge includes knowledge of design procedures, shortcuts, and so on, as well as about designed objects and their attributes. Designers think about design processes when they *begin* to sketch and draw the objects they are designing. A complete representation of designed *objects* and their attributes requires a complete representation of design *concepts*—e.g., design intentions, plans, behavior, and so on—that are harder to describe or represent than are physical objects.

Several languages or representations are used in design [5, 32]:

- *verbal* or *textual statements* are used to articulate design projects, describe objects, describe constraints or limitations, communicate between different members of design and manufacturing teams, and document completed designs;
- *graphical representations* provide pictorial descriptions of designed artifacts such as sketches, renderings, and engineering drawings;
- *shape grammars* provide formal rules of syntax for combining simpler shapes into more complex shapes;
- *features* enable the aggregation and specialization of specified geometrical shapes that are often identified with specific functions;
- *mathematical* or *analytical models* express some aspect of an artifact's function or behavior, which is often derived from *physical* principle(s);
- *numbers* represent discrete-valued design information (e.g., part dimensions) and parameters in design calculations or within algorithms representing a mathematical model.

Designers not only think in several languages; they also communicate with design team members and other stakeholders in these various languages. This in turn enables the study of design languages in the interactions of design teams in academic, research and industrial settings. Thus, researchers have studied:

- *the roles of textual language* in the work of design teams by relating design creativity to the number of noun phrases generated by design teams during conceptual design [33];
- *computational text analysis* as a means for characterizing the performance of engineering design teams and complementing the psychometric techniques that rely on surveys and interviews [34–38];
- *cyclical semantic coherence* of student design teams that supported the hypothesis that high-performing design teams cycle between divergent and convergent patterns of thinking and questioning [39];
- *sketching activities of the individual experience* of the design process [40], and supporting analysis, short-term memory, communication, and documentation [41];
- *sketches in group settings* that showed varying patterns of sketching behavior over the design process, as well as statistically significant correlations between sketching metrics and product and process outcome measures, including the assessment of variety as a measure of the explored solution space during the idea generation process [42, 43].

Design thinking in a team environment

Constructivist theories of learning recognize that learning is a social activity [44], and both cornerstone and capstone project-based courses are seen as opportunities to improve students' ability to work in teams, as well as their communication skills [45–49]. In addition, early researchers in design have long emphasized that the early stages of the design process are 'inherently argumentative', requiring the designer to continually raise questions of and argue with others over the advantages and disadvantages of alternative responses [50]. Similarly, Bucciarelli [51] defined 'design as a social process' in which teams define and negotiate decisions, and Minneman [52] reinforced Bucciarelli's view that ambiguity and negotiation are inherent to design constituting a condition and a mechanism for understanding and structuring design activity.

Researchers have also looked at the role that gender plays in design education and in design teams (e.g., [53]), and at the impact of diversity on team performance considered six diversity factors: gender, ethnicity, years of experience, technical discipline, Myers-Briggs type, and distance from campus [54]. There is also a wide body of research in design practice and in design learning on the use of psychometric measurements of personality type, such as the Myers-Briggs Temperament Indicator (MBTI), to analyze and predict the behavior and likelihood of success of teams [55, 56], and these techniques have been successfully applied to forming design teams in engineering classes [57, 58]. These investigations into team behaviors are detailed more extensively in [5].

Design is also a good context for ethics and for assessing societal impacts

The ABET general engineering criteria target the social aspects of engineering education at several levels [59]:

- criterion (c): 'an ability to design a system, component, or process to meet desired needs'
- criterion (d): addresses the need to function on multi-disciplinary teams
- criterion (f): social and ethical responsibilities
- criterion (g): communication skills
- criterion (h): addresses global and societal impact

The previous discussion in this section—as well as its more detailed source [5]—make clear how many of these social goals and aspects are reached with the aid of design courses. It is worth noting briefly that design courses have been seen as a very viable context in which to elaborate both ethical issues in engineering practice in part because of the choice of projects [10, 60], and in part because of the logical similarities of the constructs of, on the one hand, mediating and choosing among different design goals, and on the other hand, mediating among conflicting obligations to the many stakeholders in the design process [61, 62].

CONCLUSIONS

A single workshop devoted to learning and engineering design will never answer, for all time, in all places, all of the questions (implicitly) raised above—and this is not because there is a shortage of talent and accomplishment in the MDW V audience. Rather, it reflects instead the persistent difficulty of these questions and of all of the underlying contexts. It is my hope that all educators, whether engineers, scientists, social scientists, or humanists, jointly recognize that the contexts for the social dimensions of engineering design are, in fact, *shared* social contexts. Further, I hope that we work together to define and explore the social contexts of engineering design education and practice, and that our dialogues will be characterized not by finger-pointing, but by careful intellectual inquiry.

The extended paper [5] from which these remarks were adapted and synthesized did discuss one major model of design pedagogy, project-based learning, as applied in two different contexts, and in several course variations. The research available on this pedagogy suggests that these kinds of courses appear to improve retention, student satisfaction, diversity, and student learning.

On the other hand, it seems evident that the elements of these kinds of courses will raise educational costs (e.g., smaller sections, involvement of senior faculty). On a macro or global scale, these costs are likely small compared to the cost of lost human talent in the engineering pipeline—yet no one has (yet) done the economic research needed to support or negate this assessment. As noted in [5], this is a very serious problem that demands much more attention from engineering department heads and engineering deans. There is a clear need to expand the number of faculty members interested in and capable of teaching design, as there is to create the facilities—such as design studios and associated shops—that are needed for modern, project-based design courses. Thus, '*the most important recommendation is that engineers in academe, both faculty members and administrators, make enhanced design pedagogy their highest priority in future resource allocation decisions*.'

However, in the longstanding academic battle between engineering scientists and analysts, on the one side, and design and synthesis researchers and educators on the other side, perhaps it can be said that those who synthesize are catching up—and may even prevail over—the reductionists, as evidenced by the ABET goals adopted in EC 2000 and listed above. The comparison with the 'old' ABET approaches could not be more stark, and so perhaps the virtues of synthesis may one day prove ascendant.

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