Engineering Design Thinking, Teaching, and Learning

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ABSTRACT

This paper is based on the premises that the purpose of engineering education is to graduate engineers who can design, and that design thinking is complex. The paper begins by briefly reviewing the history and role of design in the engineering curriculum. Several dimensions of design thinking are then detailed, explaining why design is hard to learn and harder still to teach, and outlining the research available on how well design thinking skills are learned. The currently most-favored pedagogical model for teaching design, project-based learning (PBL), is explored next, along with available assessment data on its success. Two contexts for PBL are emphasized: first-year cornerstone courses and globally dispersed PBL courses. Finally, the paper lists some of the open research questions that must be answered to identify the best pedagogical practices of improving design learning, after which it closes by making recommendations for research aimed at enhancing design learning.

Keywords: design thinking, project-based learning, cornerstone courses, classroom as laboratory

I. INTRODUCTION

Design is widely considered to be the central or distinguishing activity of engineering [1]. It has also long been said that engineering programs should graduate engineers who can design effective solutions to meet social needs [2]. Despite these facts, the role of design in engineering education remains largely as stated by Evans et al. in 1990: "The subject [of design] seems to occupy the top drawer of a Pandora's box of controversial curriculum matters, a box often opened only as accreditation time approaches. Even 'design' faculty—those often segregated from 'analysis' faculty by the courses they teach—have trouble articulating this elusive creature called *design*" [3]. Design faculty across the country and across a range of educational institutions still feel that the leaders of engineering departments and schools are unable or unwilling to recognize the intellectual complexities and resources demanded to support good design education [4].

Historically, engineering curricula have been based largely on an "engineering science" model over the last five decades, in which engineering is taught only after a solid basis in science and mathematics. (The "engineering science" model is sometimes unfairly characterized as the "Grinter model," an attribution that ignores many other recommendations in the Grinter report [5], some of which are being independently revived today.) The first two years of the curriculum—which in many respects have changed little since the late 1950s [6]—are devoted primarily to the basic sciences, which served as the foundation for two years of "engineering sciences" or "analysis" where students apply scientific principles to technological problems. The resulting engineering graduates were perceived by industry and academia as being unable to practice in industry because of the change of focus from the practical (including drawing and shop) to the theoretical [7]. What is now routinely identified as the *capstone (design) course*[1] eventually became the standard academic response, with the strong encouragement of the ABET engineering accreditation criteria [7]. The capstone course has evolved over the years from "made up" projects devised by faculty to industry-sponsored projects where companies provide "real" problems, along with expertise and financial support [7, 8].

The infusion of first-year design courses—later dubbed *cornerstone (design) courses* [9] in the 1990s—was motivated by an awareness of the curricular disconnect with first-year students who often did not see any engineering faculty for most of their first two years of study [10, 11]. During this period first-year project and design courses emerged as a means for students to be exposed to some flavor of what engineers actually do [12–14] while enjoying an experience where they could learn the basic elements of the design process by doing real design projects (e.g., [15, 16]).

Though the presence, role, and perception of design in the engineering curriculum have improved markedly in recent years, both design faculty and design practitioners would argue that further improvements are necessary [4, 17]. There have even been formal proposals for curricular goals and assessment measures

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[1] The *capstone course* is a U.S. term for design courses typically taken in the senior year. The term *cornerstone* is a recent U.S. coinage for design or project courses taken early (e.g., first year) in the engineering curriculum. It was intended to draw a distinction from and preserve the mataphor of the capstone course.

for design-based curricula (e.g., MIT's Conceive-Design-Implement- Operate (CDIO) initiative [18]). This argument is driven in part by a widespread feeling that the intellectual content of design is consistently underestimated. Thus, section II provides definitions of both engineering and design to set a context for what follows. It then reviews research on design thinking as it relates to how designers think and learn, which is an important reason that design is difficult to teach. Design thinking reflects the complex processes of inquiry and learning that designers perform in a systems context, making decisions as they proceed, often working collaboratively on teams in a social process, and "speaking" several languages with each other (and to themselves). Assessment data on these characterizations are also discussed, although some of that data derives from studies in contexts other than design.

Section III reviews research on project-based learning (PBL)[2] as one of the more effective ways for students to learn design by experiencing design as active participants. Section III also outlines some of the pedagogical issues and some assessment of cornerstone engineering PBL and design courses and globally dispersed PBL courses.

Section IV identifies questions on research on design thinking and design theory, on their relationship to design pedagogy, and on design teaching and learning that remain open and worthy of further study. Section V closes by making recommendations for further study and action.

II. ON DESIGN THINKING

Definitions of engineering abound, as do definitions of design. Sheppard's characterization of what engineers do is especially relevant: engineers "scope, generate, evaluate, and realize ideas" [2]. Sheppard's characterization focuses on how engineers think and embraces the heart of the design process by highlighting the creation (i.e., scoping and generation), assessment, and selection (i.e., evaluation), and the making or bringing to life (i.e., realization) of ideas. Pahl has argued that the knowledge of technical systems or analysis is not sufficient to understand the thought processes that lead to successful synthesis or design, and that studying those thought processes is critical to improving design methodologies [20].

What does the word "design" mean in an engineering context? Why is this complex, fascinating subject so hard to teach? The definition of design adopted here sets a course for answering these questions:

> *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 promotes engineering design as a *thoughtful* process that depends on the systematic, intelligent generation of design concepts and the specifications that make it possible to realize these concepts [16, 21]. While creativity is important, and may even be teachable, design is not invention as caricatured by the shouting of "Eureka" and the flashing of a light bulb. Design problems reflect the fact that the designer has 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. The design process is itself a complex cognitive process.

There are many informative approaches to characterizing design thinking, some of which are now detailed. These characterizations highlight the skills often associated with good designers, namely, the ability to:

- tolerate ambiguity that shows up in viewing design as inquiry or as an iterative loop of divergent-convergent thinking;
- maintain sight of the big picture by including systems thinking and systems design;
- handle uncertainty;
- make decisions;
- think as part of a team in a social process; and
- think and communicate in the several languages of design.

A. Design Thinking as Divergent-Convergent Questioning

Asking questions emerges as a beginning step of any design project or class in the *problem definition* phase [16]. No sooner has a client or professor defined a series of objectives for a designed artifact than the designers—whether in a real design studio or a classroom—want to know what the client really wants. What is a safe product? What do you mean by cheap? How do you define the best? Questioning is clearly an integral part of design.

On the other hand, the majority of the educational content taught in today's engineering curricula is an *epistemological* approach, *systematic questioning*, where known, proven principles are applied to analyze a problem to reach verifiable, "truthful" answers or solutions. While it seems clear that systematic questioning describes analysis well, does it apply in a design context? One would expect an affirmative answer to this question, in part because design educators already argue that the tools and techniques used to assist designers' creativity are "…ways of asking questions, and presenting and viewing the answers to those questions as the design process unfolds" [16]. Further, since the accepted basic models of the design process (see, for example, Figure 2.4 of [16]) show iterative loops between various stages of design, it is clear that questioning of various kinds takes place at varying stages of the process.

Aristotle proposed that "the kinds of questions we ask are as many as the kinds of things which we know" [22]. In other words, *knowledge resides in the questions that can be asked and the answers that can be provided*. Dillon identified a *sequence of inquiry* that highlights a hierarchy in Aristotle's approach: certain types of questions need to be asked and answered before others can be asked [23]. For instance, it would be unsound, misleading, and ineffective to question or reason about the cause of a phenomenon *before* verifying its existence and understanding its essence. Aristotle's ordering thus reveals a *procedure*, which constitutes the inquiry process in an epistemological context. Taxonomies of this procedure or inquiry process have been extended to computational models [24], to the relationship between question asking and learning [25], and to the types of questions students ask during tutoring sessions [26].

One of the major strengths of today's engineering curricula is their ability to implicitly convey to engineering students that Aristotelian procedure as a framework for approaching engineering

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[2] The acronym PBL is also used in the education literature—originally in medical education and more recently in discussions of college curricula such as business and law—to signify *problem-based learning*, in which abstract theoretical material is introduced in more "familiar," everyday problem situations [19]. The two PBL's have some common goals and implementation features, but they are nonetheless distinct pedagogical styles.

problems. In fact, the incidence of a specific class of questions, termed deep reasoning questions, has been shown to correlate positively with student learning in a science context as measured by a test score [27]. If deep reasoning questions are indeed related to learning performance when it comes to comprehending and reasoning about a specific body of material, then an effective inquiry process would follow "Aristotle's procedure," where lower-level questions related to the existence, essence, and attributes of a phenomenon precede the deep reasoning questions related to the phenomenon itself.

The nature of systematic questioning in a design context[3], and whether it differs from the epistemological inquiry process, has also been considered by observing and analyzing how designers think and question [27]. More than 2,000 questions posed by designers in team meetings (in a series of quasi-controlled laboratory experiments in which 36 designers worked in teams of three [27]) were extracted and coded. Interestingly, 15 percent of the questions could not be placed in any of the categories identified in any published taxonomies of questions, which suggests the possibility that designers' inquiry and thinking processes might have unique, identifiable characteristics.

A common premise of the foregoing discussion is that a specific answer, or a specific set of answers, exists for a given question. Such questions are characteristic of *convergent thinking*, where the questioner attempts to converge on and reveal "facts." Therefore, answers to converging questions are expected to be hold *truth value*, that is, to be verifiable. Deep reasoning questions are such questions.

Questions that are asked in design situations, however, often operate under a diametrically opposite premise: for any given question, there exist multiple alternative known answers, regardless of being true or false, as well as multiple unknown possible answers. The questioner intends to disclose the alternative known answers and to generate the unknown possible ones. Such questions are characteristic of divergent thinking, where the questioner attempts to diverge from facts to the possibilities that can be created from them. Eris termed these types of questions generative design questions [27]. The questioner is not necessarily concerned with the truthfulness or verifiability of potential answers when posing a generative design question.

The key distinction between the two classes is that convergent questions operate in the knowledge domain, whereas divergent questions operate in the concept domain. This has strong implications for teaching conceptual design thinking since, as the recently proposed concept-knowledge theory [29] also argues, concepts need not have truth value, whereas knowledge does. Design thinking is thus seen as a series of continuous transformations from the concept domain to the knowledge domain. As Vincenti observed, such questioning and thinking also reflect the process by which designers add to the store of engineering knowledge [30].

The significance of the transformations between the concept and knowledge domains is further supported by the finding that the combined incidence of deep reasoning questions and generative design questions correlate with performance in obtaining design solutions [27]. On a related note, there is evidence that the contents of questions, as manifested in the linguistic evolution of the noun phrases contained in design documents, correlate with design performance [31, 32].

Therefore, effective inquiry in design thinking includes both a convergent component of building up to asking deep reasoning questions by systematically asking lower-level, convergent questions, and a divergent component in which generative design questions are asked to create the concepts on which the convergent component can act. (The decision-based approaches to design considered in section II.C can be considered a dimension of the convergent component.)

Teaching divergent inquiry in design thinking is neither recognized clearly nor performed well in engineering curricula. For example, it is not acceptable for a student to respond to a final exam question in an engineering science course by providing multiple possible concepts that do not have truth value. Indeed, students are expected to engage in a convergent process by formulating a set of deep reasoning questions and working to *the* (unique) answer. Students' ability to converge is being positively assessed when partial credit is given for the "thought process," even if the answer is wrong. In this context, engineering curricula may be characterized as follows:

- One of the main strengths of engineering curricula is their perceived effectiveness in conveying Aristotle's epistemological, convergent inquiry process. It promotes the ability to reason about knowledge associated with mathematics and sciences, which is construed as the engineering science or reductionist model.
- Divergent inquiry takes place in the concept domain, where concepts or answers themselves do not have truth value, that is, they are not necessarily verifiable. This is the design or synthesis model. It often seems to conflict with the principles and values that are at the core of the predominantly deterministic, engineering science approach.

The foregoing discussion raises the following question: Can the now more-formal identification of both divergent thinking and design as an iterative divergent-convergent process be used to develop better pedagogical approaches to both engineering design and engineering analysis?

B. Thinking About Designing Systems

In recent decades designers have helped develop an increasingly complex, human-built world that includes ambitious large-scale engineering projects [33]. At the same time, designers are making engineered products and systems increasingly complex as they work to improve robustness by increasing the number of components and their interdependencies [34]. Further, designers are now required to expand the boundaries of the design to include such factors as environmental and social impacts in their designed systems [35]. These trends suggest that engineering designers need skills that help them cope with complexity. In response, many universities have created specialized programs for system design, systems engineering, and closely related areas [36]. This section reviews research on the system design and systems thinking skills that good designers exhibit and that engineering students should experience. The specific aspects of systems thinking discussed here—recognizing the systems context, reasoning about uncertainty, making estimates, and

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[3] The underlying premise of the notion that there exists an inquiry process in design thinking is consistent with empirical evidence presented by Baya [28]. While analyzing the information needs of designers in order to identify specifications for a design information utility, Baya made a key observation by stating that the questioning behavior of designers is not random, and that they ask new questions after reflecting on information received in answer to other questions [28].

performing experiments—might be characterized as desirable habits of mind that also reflect the notion of convergent-divergent thinking discussed just above.

1) Thinking about system dynamics: A hallmark of good system designers is that they can anticipate the unintended consequences emerging from interactions among the multiple parts of a system. This kind of foresight is essential for designing engineering systems and managing the design process. A large body of work has been conducted on reasoning about system dynamics under the rubrics of systems thinking [37] and system dynamics. An excellent review of system dynamics and learning is provided in [38, 39]. Unfortunately, this skill is not common and can be difficult to learn. Sweeney and Sterman showed that most management graduate students at one highly competitive school could not effectively reason about the dynamics of simple systems, such as tubs of water filling and draining or inventory rising and falling as customer demand and manufacturing capacity vary [40]. Engineering and mathematics education was a significant benefit for the simpler tasks studied, but was far from significant in its beneficial effects on the more difficult tasks. Many different teaching methods have been proposed to improve people's abilities to reason qualitatively about feedback, stocks, and flows in systems. One hands-on exercise, the "beer game," has been used widely to expose people to the issues of unintended consequences arising from system dynamics. Unfortunately, in a group of human subjects in a recent study [40], experience in the "beer game" did not lead to statistically significant improvements in the performance of most system dynamics tasks. Recognizing that there are many unresolved difficulties in this area, Doyle has 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 [41]. Some portions of this research agenda might profitably be undertaken by researchers in engineering education.

2) Reasoning about uncertainty: Engineering design is conducted with imperfect models, incomplete information, and often with ambiguous objectives as well. The effects of such uncertainties are even more prominent in the design of systems. Some have argued that undergraduate engineering curricula greatly underemphasize the application of probability and statistics in engineering (e.g., [42]). Numerous studies in cognitive psychology have shown that people are prone to serious errors in probabilistic and statistical thinking, such as the neglect of prior probabilities, insensitivity to sample size, and misconceptions of regression [43]. Formal mathematical training in probability and statistics reduces some errors but has little effect on others, e.g., systematic underestimation of uncertainty [44]. A new statistics concept inventory (SCI) has been developed that has revealed that statistics courses did not significantly improve people's conceptual understanding of statistics [45]. However, recent research suggests some promising new approaches. Communicating possible outcomes in term of *frequencies*—rather than probabilities—can significantly improve the validity of inferences drawn and the effectiveness of their communication [46].

Educators in engineering and related disciplines have been working to overcome these difficulties by emphasizing conceptual understanding, using more hands-on teaching methods, and using more graphics and simulations (e.g., [47–49]). Wood argues persuasively that there is much further to go and that uncertainty should be made central to design education [50]. He suggests that this be done by including (1) probability and statistics courses early in the curriculum, (2) uncertainty in engineering analysis courses, (3) more emphasis on experimentation as a design activity, and (4) consideration of uncertainty in technical electives and humanities courses [40]. Such curriculum changes may be inadequate without research aimed at continued improvements in probabilistic and statistical thinking for engineering design. One widely acknowledged path to improvement is to make better use of modern computational tools to support probabilistic thinking. A lesser-known path to improvement is to leverage recent research in cognitive psychology and attack identified human weaknesses in probabilistic reasoning by better understanding and exploiting remarkable human strengths in visual processing, long-term memory, and pattern recognition.

3) Making estimates: One of the challenges of system design is that, as the number of variables and interactions grows, the system stretches beyond designers' capability to grasp all of the details simultaneously. One strategy for bringing a system back within the limits of human mental capacity is to focus selectively on a limited number of factors, preferably the most important ones. Good system designers are usually good at estimation—they can efficiently determine the relative sizes of physical parameters and identify those that can safely be neglected, at least for specific purposes. Unfortunately, engineering graduates are generally not good at estimation. Linder administered a test in which engineering students were asked to estimate a physical quantity within five minutes, for example, the energy stored in a battery and the drag force on a bicycle and rider at a given speed [51]. The undergraduates' estimates on each question varied greatly, with inter-quartile ranges of roughly three to five orders of magnitude, depending on the question. This poor performance seems to be related to a weak conceptual understanding of basic engineering science and a limited ability to form appropriate analogies. Engineering education currently emphasizes sophisticated methods for precise calculation and thus may underemphasize skills related to approximation [51]. Teaching methods and curricular designs for improved approximation skills represent a promising area for research and development.

4) Conducting experiments: The design of systems is rarely accomplished exclusively by applying fundamental scientific principles. In most cases, the design of systems also requires some use of empirical data and experimentation. This fact is driving a trend to teach engineers the design of experiments so they can more efficiently plan experiments and analyze and understand the results. These techniques are now widely taught in industry through "six sigma" programs, as well as through more traditional college and professional education programs. The methods of experiment design are now widely disseminated and are having a significant impact throughout industry. However, the statistical methods of experiment design alone will not be sufficient for engineers to learn effectively through experimentation. Box recently argued that an overly rigid adherence to statistical measures of optimal design can have a deleterious effect on the learning process [52]. Box also argues 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 understanding and models based on data. There is potentially great promise in research on how to teach engineers to make coordinated use of engineering models and experiments.

C. Making Design Decisions

All agree that designers make decisions throughout the design process, and several decision-centric design methods and frameworks have been developed in recent years [53–59]. The common underlying concept in these decision-based design frameworks is that design is a rational process of choosing among design alternatives. Some have questioned whether design decisions are scientifically or mathematically sound. Hazelrigg has argued that to make engineering design a truly rational process that produces "the best possible results…, a mathematics of design is needed…based on the recognition that engineering design is a decision-intensive process and adapting theories from other fields such as economics and decision theory" [53]. He extended his argument by leveraging decision theory to construct a set of axioms for designing and to derive two theorems that could be applied to construct statistical models that would account for uncertainty, risk, information, preferences, and external factors such as competition—the elements of game theory [60]. This approach arguably results in numerous decisions, only one of which would be optimal. Hazelrigg concluded that the axiomatic approach yields a more accurate representation and produces results having a higher probability of winning in a competitive situation.

Radford and Gero also articulated a decision-centric view [54] but used a deterministic—as opposed to Hazelrigg's probabilistic—model that accounts for ambiguity through optimization. They also stressed that goals are an essential feature of design and necessitate decisions as to how they should be achieved. They further argued that exploring the relationship between design decisions and the performance of the resulting solutions is fundamental to design, with optimization used to introduce goal-seeking directly into design exploration.

Dieter demonstrated the relevance of the application of existing decision-centric views to evaluating and choosing between alternative design concepts [55]. He constructed a decision matrix to determine the intrinsic worth of outcomes associated with competing design concepts. Dieter's method is based on utility theory and formalizes the development of values in decision making. It is similar to the widely used "Pugh selection chart" methodology [56–59]. He also used probability theory to demonstrate the application of decision trees to design concept selection.

The role of decision making in design—and particularly the identification of design as decision making—has not been without critics. For example, some of the underlying decision-theoretic premises (e.g., the Arrow Impossibility Theorem) are not viewed as appropriate models for describing design processes [61]. Further, whereas a premise of decision theory is that the quality of a decision cannot be assessed by a post facto evaluation of its outcome, it is hard to imagine a designer who is not focused on the outcome of design decisions being made [62]. Further, the decision-based design framework assumes that designers make critical decisions only *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. Decision-based design cannot account for or suggest a process for how concepts and alternatives are generated—and this is often regarded as the most creative and hard-to-model aspect of design thinking.

Some decision theorists acknowledge these limitations by recognizing that decision analysis can only be practiced after a certain point. Howard asked, "Is decision analysis too narrow for the richness of the human decision?" [63]. He then argued that "framing" and "creating alternatives" should be addressed before decision analysis techniques are applied to ensure that "we are working on the right problem." Howard also observed 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" [63]. Howard might just have well been talking about the design process, for it is the framing of design decisions that is the most engaging part of doing design, as well as the most difficult to teach.

D. Design Thinking in a Team Environment

To an increasing degree, design is being recognized and taught as a team process with multiple socio-technological dimensions [64]. One practical reason is that the ABET general engineering criteria target the social aspects of engineering education at several levels. In addition to criterion 3(c), "an ability to design a system, component, or process to meet desired needs," criterion 3(d) addresses the need to function on multidisciplinary teams, criterion 3(f) social and ethical responsibilities, criterion 3(g) communication skills, and criterion 3(h) addresses global and social impact. Constructivist theories of learning recognize that learning is a social activity [76], 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. As a result, campuses now incorporate many of these dimensions in their design classes, ranging from cornerstone to capstone [65–72].

But in fact, Horst Rittel, an early researcher in the design sciences, long ago emphasized that the early stages of the design process are "inherently argumentative," requiring the designer to continually raise questions—not unlike the Aristotelian approach detailed in section II.A—and argue with others over the advantages and disadvantages of alternative responses [73]. Similarly, Bucciarelli defined "design as a social process" in which teams define and negotiate decisions [74]. He argued that each participant possesses an ingrained set of technical values and representations that act as a filter during design team interactions, and that the resulting design is an intersection—not a simple summation-of the participants' products. This framing of design was used to develop a number of pedagogical exercises, including the Delta Design jigsaw exercise [75], to promote multidisciplinary discourse and constraint negotiation.

Minneman reemphasized Bucciarelli's views on the role of ambiguity and negotiation: they are inherent to design and constitute a condition and a mechanism for understanding and structuring design activity [76]. Minneman also argued that those views shift the focus of group design support onto communication systems and that "design education should be refocused on teaching designers to better function in group situations."

Several researchers have looked at the role that gender plays in design education and in design teams [77–82]. Agogino examined students' gendered perceptions of the design process in the freshman/sophomore class *ME39D: Designing Technology for Girls and Women* at the University of California at Berkeley [83]. The course covered gender issues associated with new product development from a human-centered design perspective. Students worked in multidisciplinary design teams and participated in interactive workshops with target users and industry sponsors. The class was one of the Virtual Development Centers sponsored by the Anita Borg Institute of Women and Technology[4] and by supporting companies in the San Francisco Bay area. Three forms of data collection techniques were used: interviews, questionnaires, and a design process assignment. Evaluation showed that students developed a strong belief that "good design" dictates that technology can and should serve all members of the potential user population, including those traditionally underrepresented with technology. Further, students showed a statistically significant level of increased confidence in technology and an increased comfort level working on design projects.

Carrillo's investigation of 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 [84]. The study demonstrated that the impact of diversity is time dependent and its results support the case for maximizing diversity. The impact of individual diversity factors could not be teased out statistically [84].

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 [85, 86]. These techniques have been successfully applied to forming design teams in engineering classes. Wilde applied Jungian typology and MBTI to the formation of student engineering design teams, showing that the likelihood of a successful design outcome is increased by forming teams consisting of members with complementary roles, a plurality of viewpoints, a neutral manager, and a "wild card" [87]. Lent et al. described the effect of *collective efficacy*, a team's beliefs about its own capabilities to work together, on the cohesion and satisfaction of the team [88]. They found that negative feelings of collective efficacy might limit outcome expectations, requiring remedial steps to promote effective teamwork.

E. 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 to serve different purposes. Yet engineering students seem to believe that mathematics is *the* language of engineering, perhaps because of the pervasive use of mathematics to formulate and solve engineering problems in the engineering-as-applied-science curriculum. As may be inferred from much of the foregoing discussion, and as will also be seen in the discussion of drawing and sketching below, design requires the use of 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 knowledge 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. In fact, the roles that languages play in design have been discussed in both philosophical and grammatical terms [20, 89, 90].

The several languages or representations used in design, both in practice and in research, include the following [91–93]:

- *verbal or textual statements* 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* used to provide pictorial descriptions of designed artifacts such as sketches, renderings, and engineering drawings;
- *shape grammars* used to provide formal rules of syntax for combining simpler shapes into more complex shapes;
- *features* used to aggregate and specialize specified geometrical shapes that are often identified with specific functions;
- *mathematical or analytical models* used to express some aspect of an artifact's function or behavior, where this behavior is in turn often derived from some physical principle(s); and
- *numbers* used to represent discrete-valued design information (e.g., part dimensions) and parameters in design calculations or within algorithms representing a mathematical model.

Researchers have studied various aspects of the roles of textual language in the work of design teams. For example, Mabogunje and Leifer measured the relation of design creativity to the number of noun phrases generated by design teams during conceptual design [32]. They extracted noun phrases from transcripts of design team meetings, finding the number of unique noun phrases generated as being directly proportional to higher levels of creativity, though not necessary successful outcomes.

Research by Dong et al. [94–96] on computational text analysis as a means for characterizing the performance of engineering design teams is intended to complement the aforementioned psychometric techniques that rely on surveys and interviews (e.g., pre-interviews, post mortems, etc.). The methodology established offers a non-intrusive means for instructors or self-managing teams [97] to delve into the behavior of the teams in real time, thereby yielding the capability to deal with the nuances of team performance as they occur rather than just at the formation of the team or at the post-mortem. Song et al. [98] took the next step in examining the oral and written histories left by the student designers through their documentation, presentation material, and e-mail communication, and then plotting the semantic coherence of these histories over the product design cycle [72]. Results from the analysis suggest a positive correlation between design outcomes and patterns of the average semantic coherence over time, as well as with variation in semantic coherence between design stages. This research provides empirical evidence of the phenomena of changing levels of coherence in "story telling" in design and in the scope of design concepts explored by design teams. The results indicated that student design teams that challenged assumptions throughout the design process, with cyclical semantic coherence, performed better than teams that had little variation over the design process. These results support the hypothesis that high-performing design teams cycle between divergent and convergent patterns of thinking and questioning.

Understanding and analyzing sketching activities are ongoing research topics within the design education and research community because sketching is an integral and important part of the design process. Sketching also provides another language or representation

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[4] http://www.iwt.org

that can be used to store design solutions and to highlight conflicts and possibilities. It can also form a basis for revising and refining ideas, generating concepts, and facilitating problem solving [99]. Therefore, sketching can have a positive impact on the quality of the designed solution and on the individual experience of the design process [100]. Serving as an aid for analysis, short-term memory, communication, and documentation [101], sketching can also facilitate and hasten the development of ideas and concepts into a successful product.

While much effort has been placed on evaluating their impact on the individual designer [99–101], fewer studies cover the use of sketches in group settings. Song and Agogino analyzed the sketching activities of new product design teams during a semester-long undergraduate class at the University of California, Berkeley [102]. This test bed was composed of thirteen design teams that varied in size from three to seven members. Two additional teams were not included in this study, as their design documentation was incomplete. The study addressed four research issues. First, what are useful metrics for characterizing design sketches? Second, how do sketching activities evolve over time? Third, are sketches indicative of the design space explored? And finally, are there any correlations between sketching activities and the outcome of the team? That is, what insights into the design process and individual experience are provided by analyzing sketching activities? Song and Agogino's analysis [102] 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.

In a detailed case study of engineering design, Yang examined the timing of sketch types as one of the factors in the design process that contributes to a design's success or failure [103]. Yang's study suggested that there is a statistically significant correlation between the quantity of early, dimensioned drawings and the graded design outcome.

Shah et al. defined *variety* as a measure of the explored solution space during the idea-generation process [104]. Ideas were grouped based on how different two ideas were from each other; the use of a different physical principle to satisfy the same function made two ideas very different. They also examined how each function was satisfied with a collection of concepts and applied a variety rating to an entire group of similar ideas rather than to an individual idea. Similarly, Song and Agogino [102] found a statistically significant multivariate correlation between the total number and variety of drawings and the performance of their student design teams, implying that both breadth and depth may be needed for effectively covering the design space and developing the best products.

III. DESIGN PEDAGOGY AND PROJECT-BASED LEARNING

Design projects have been used as vehicles to motivate and integrate learning (e.g., Georgia Tech's Learning by Design^{TM} [105]), and cornerstone project-based courses are also seen as a means to enhance students' motivation and their retention in engineering, in part because they introduce engineering content and experience early in the curriculum, in part because they also put first-year students into direct contact with engineering faculty. Brereton [106] studied how engineering students learn and develop engineering intuition by continuously shifting their thinking paradigm from engineering theory to interaction with hardware. She demonstrated that "engineering fundamentals are learned through activities at the border that involve continually translating between hardware and abstract representations," suggesting the application of convergent-divergent thinking in a hands-on *project* context.

Both cornerstone and capstone courses are increasingly referred to as providing design or project *experiences*, thus exemplifying Kolb's model of experiential learning [107]. In addition, and for several reasons, ethics and social impact have become part of the fare of both cornerstone and capstone courses (see [16], for example, and [108]). One particular dimension of this spawned the new descriptor of service-learning courses. Students in some early cornerstone courses (e.g., Harvey Mudd's E4 [15]) worked only on projects for external, not-for-profit clients, in part "to inform students about the numerous engineering challenges available to them in arenas other than aerospace . . . defense . . ." Such emphasis on engineering to meet people's needs—recall Sheppard's characterization of engineering [2]—is well received by engineering students and has been institutionalized as service learning in programs such as Purdue's highly regarded Engineering Projects in Community Service (EPICS) program [109].

Given Brereton's suggestion of a dialectic between hardware and models [106], Kolb's notion of learning through experience [107] and the fact that real-world engineering projects come to fruition only through the efforts of teams focusing on real projects, it is hardly surprising that emulating such experiences in the classroom seems desirable. Indeed, as will now be shown, using the project in the classroom has recently turned out to be a major innovation in design pedagogy.

A. What is Project-based Learning?

The 1997 National Science Foundation report, *Systemic Engineering Education Reform: An Action Agenda* [110], was a call for reform in engineering education that emphasized, among other things, teamwork, project-based learning (PBL), and close interaction with industry. Changes in engineering education were inspired by employers who indicated a need for engineers who are not only experts in their domain, but who are also adept communicators, good team members, and lifelong learners [111, 112]. For the purposes of this review it is convenient to begin with the founding of the Aalborg University in Denmark in 1974 as, apparently, the first (and only) institution of higher education founded on the pedagogic premise of project-based learning [113, 114]. Aalborg's working definition was and remains "Problem-Oriented, Project-Organized, Learning." The Aalborg premise is that *project-organized education* is multidisciplinary by nature, and it can be divided into two main themes that seemingly parallel the idea of integrating divergent and convergent thinking [113, 114]:

- *design-oriented* project-organized education deals with *know how*, the practical problems of constructing and designing on the basis of a synthesis of knowledge from many disciplines; and
- *problem-oriented* project-organized education deals with *know why*, the solution of theoretical problems through the use of any relevant knowledge, whatever discipline the knowledge derives from.

The engineering and science curricula at Aalborg use both kinds of project-organized education. The project work in Aalborg's undergraduate programs largely involves the design-oriented approach, while graduate studies mainly involve the problem-oriented approach.

On the occasion of the twenty-fifth anniversary of the university's founding, a report detailing the conclusions of an international assessment review was issued [115]. Of the many detailed findings reported, three of the most striking are:

- "The freshmen's involvement with project work was not seen to be as effective as it may… since the students did not have the technical knowledge or tools to benefit fully from the experience… [which] could be outweighed by the benefits of the early establishment of a group culture… [115, p. 33]."
- "… the work conducted by the students during their theses (capstone projects)… [is] of a quality equivalent to that of institutions with which Aalborg University is competing internationally [115, p. 44]."
- "… the superiors of the employed engineers graduated from the two universities (Aalborg and Copenhagen, DE) assessed there to be no differences between the general qualifications of the graduate engineers, while graduates from Aalborg were assessed to have significantly better qualifications in co-operation [115, p. 45]."

These assessments suggest that the formal adoption of a PBL-directed curriculum produces results that are similar to, even indistinguishable from, those obtained with the typical U.S. approach, except with regard to the "significantly better qualifications in co-operation." This is an attribute that U.S. employers say they want (e.g., [17]), but there appear to be no published data on this point or on how individual companies rate curricula or schools according to the performance of their employees. While companies are said to do such ratings and assessments, and while companies such as General Motors and Boeing have had "key schools" programs, none have published data that identify preferred, school-specific curricular outcomes.

PBL does address one of the key issues in the cognitive sciences, *transfer*, which may be defined as the ability to extend what has been learned in one context to other, new contexts [116]. This is an important component of engineering competency development [117]. While the design studio has long been a centerpiece of design-thinking and pedagogy outside engineering, it took the medical community to lead engineers back to thinking formally about PBL. The use of problem-based learning in medical schools demonstrated that first-year students were substantially better diagnosticians, i.e., practitioners, than those taught by lecture [118]. (It is interesting that Harvey Mudd's Engineering Clinic program was so named because its founders wanted to emulate the last two years of medical school curricula that are clinic based [8].) Today, the professions are converging; engineering, medicine, law, and business are moving toward similar project- and problem-based pedagogic frameworks. Emerging evidence suggests that PBL encourages and supports collaborative work [115] and that it improves retention and enhances design thinking (section III.B). However, the need remains to extend the results already obtained and to demonstrate as well PBL's value in increasingly authentic design scenarios that typically include participation across disciplines, as well as across geographical and temporal boundaries.

B. Introducing Project-based Learning and Design Thinking in the First Year

As noted above, there is an emerging trend of first-year, cornerstone courses, some of which are solely (pure) "design" courses and almost all of which incorporate a team-based project. There is a wonderful diversity about their implementations. For example, when the "E4" course was introduced at Harvey Mudd in spring 1992, each team of four students worked on just one semester-long project for an external, not-for-profit client. Several teams worked on each project in parallel, with their final presentations providing a graphic and often colorful demonstration of open-ended design [15]. Lectures on design methods, team dynamics, and ethics were conducted concurrently. Now E4 is offered in a studio mode [119], and student teams work on three projects: a project chosen by the faculty to provide a basis for learning the design tools (four to five weeks); a dissection or reverse engineering [120–122] project (two to three weeks); and a main design project for an external client (approximately seven weeks). Northwestern University has developed a two-quarter project-based course, co-taught by a team of engineering and writing faculty [123], that combines design and technical writing. Other schools (e.g., Penn State) combine design with graphics [124].

These cornerstone courses are similar to many capstone design courses, but they differ markedly in their tendency to focus more heavily on conceptual design methods and less on discipline-specific artifacts (e.g., cars in mechanical engineering, chips in electrical engineering), in part because there are now textbooks for such courses (e.g., [16, 111]) and in part because first-year students can do reasonable conceptual design without the detailed technical knowledge they acquire only later in the curriculum. In fact, there is a strong belief that first-year, cornerstone courses:

- enhance student interest in engineering;
- enhance student retention in engineering programs;
- motivate learning in upper division engineering science courses; and
- enhance performance in capstone design courses and experiences.

Beyond the anecdotal data (e.g., [125]), there is hard evidence that supports these assertions [126–138]. Assessment and outcomes research has been done much more vigorously in recent years (see [126] for a comprehensive survey). There have been many studies of design per se (e.g., [127, 128] and many of the references in sections II and IV), and there are some assessment data on the impact of cornerstone project and design courses.

Olds and Miller reported that "average" engineering students at the Colorado School of Mines recruited into a pilot integrated curriculum intended to allow students "to discover and explore important connections among the humanities, physical and social sciences, and engineering subjects they studied in their first year at CSM," showed a nine percent increase in the five-year graduation rate, with much of the benefit being attributed to mentoring by senior faculty and the development of a sense of community [129]. Richardson and Dantzler noted that the retention rates of students at the University of Alabama who take engineering courses in their first-year have improved as much as sixteen percent [130]. Similarly, Texas A&M [131] and the University of Florida [132] report improvements in retention rates—especially among women and underrepresented minorities—attributable to building a sense of community among first-year students and mentoring by senior faculty. Similar results are reported by the Gateway coalition of eight schools (Columbia, Cooper Union, Drexel, NJIT, Ohio State, Polytechnic, South Carolina, USC) for second-year retention rates of engineering students who have taken an integrated science program and a project-based course in their first year; second-year retention rates compared with national rates were 86 percent to 67 percent for minority students, 90 percent to 88 percent for women students, and 86 percent to 70 percent for all students [133].

Fromm, director of the Gateway coalition, has estimated that the "project-based cornerstone course played a significant role in attaining the results" cited above [134]. While design courses were not specifically part of all curriculum changes and assessments, some type of project was generally included. Knight, Carlson, and Sullivan studied the impact of the First-Year Engineering Project (FYEP) course at the University of Colorado at Boulder (CU) [135]. The CU course included "practical considerations of the design process, experimental testing and analysis, project management, oral and written communication, and working in multidisciplinary teams"—in other words, all of the elements of a first-year design course [15]. Retention gains ranging from three percent to 54 percent were reported at CU, with the largest being among women (27 percent), African-American (36 percent), and Latino (54 percent) students [135]. The smallest gains were among students of Asian descent (three percent). Similarly, at Carnegie Mellon University, where first-year courses are introductions to the disciplines that typically have several team-based project components and thus have significant design content, such courses have had a significant impact on retention in the engineering program [136]. First-year retention rates went from about 80 percent to about 97 percent since the introduction of team-based project courses. While all of this gain cannot be solely attributed to these courses, they reportedly have provided a better basis for students to make choices of disciplines, and to gain valuable engineering experience and an appreciation for the math and science courses they are taking as pre- and co-requisites to their engineering courses [137]. Note that this inference is similar to that drawn for the Gateway coalition experience [134].

In short, while there is no definitive data specific to design courses, and while there are different views of the proper metric for assessing retention (e.g., see the discussion in [130]), there seem to be enough data to support the thesis that a design course or something that contains many of its elements—including projects, teams, and written and oral communication—can produce very positive changes in engineering student retention rates.

In terms of other measures of potential benefits of first-year *design* courses, little data are available. Purdue's EPICS program reports that students regarded teamwork, communication, and time management and/or organization as "the three most valuable things ... learned" from having taken the EPICS course [137]. The skills acquired here are also just the "soft" skills that ABET's engineering criteria are trying to promote. These results are quite consistent with—and supportive of—the anecdotal data heard from most teachers of such courses.

Two other aspects of design project implementations are worth noting. First, a number of design contests have emerged in the last two decades as a popular activity in engineering education that often generates a lot of publicity [138]. These contests sometimes include outreach to high school students (e.g., FIRST), are often sponsored by professional societies (e.g., AIAA, ASME, SAE), and within engineering programs are sometimes done as extracurricular activities or for credit within capstone or other courses [138].

Second, cornerstone courses are sufficiently unusual in the recent history of engineering schools and are taught by a relatively small number of engineering faculty members. Generally, faculty members who have not dedicated themselves to this pedagogical vision do not find it easy or comfortable because of the amount of effort involved and the kinds of activities they are required to do [139]. In general, the limited data available suggest that design faculty members generally have a more difficult time with advancement and other rewards in academe [4]. The metric of faculty involvement suggests that the long-term sustenance of cornerstone and other design courses might be problematic, regardless of how good the educational and retention results are.

C. Project-based Learning on a Global Scale

Today's engineer must design under—and so understand at a deep level—constraints that include global, cultural, and business contexts. They are part of the new "fundamentals" [140–142]. Thus, educators must look beyond the limits of their own institutions toward a global network for design education. As will emerge in greater detail in section IV.B below, a global network is defined as a network that connects geographically dispersed design teams and (possibly) clients that are connected by appropriate technological means. This section explores some of the emerging research issues on project-based learning in such global networks.

Few evidence-based results have been reported on courses that are taken over a geographicallydispersed network [143]. There are, however, some reasons to be encouraged. One data point is a comparison of results achieved by local and global teams in the Lincoln Arc Welding Graduate Design Competition, in which the notable difference was that globally distributed teams consistently produced better documentation of both their products and their processes [144]. A preliminary study at the Norwegian University of Science and Technology at Trondheim indicates that maintaining an e-mail logbook is a strong facilitating factor in students' development of their academic identity, as well as their prowess in academic writing [145]. While not strictly global engineering, the subjects were 150 doctoral students whose work is typically global in reference. Challenged to make their Software Project Management (SWPM) curriculum globally accessible, researchers at the University of Texas, Austin, report that careful attention to learner-centric project pedagogy helped them transition a local course into a globally accessible e-learning curriculum that has graduated hundreds of satisfied corporate client employees [146].

Dutta et al. [147] report that students in a *Global Product Development* course participated in an anonymous, online survey composed of twenty questions. More than 80 percent of the respondents stated that the global team approach "added tremendous value to the course" and that they would participate in a similar course again. Respondents also reported (64 percent) that videoconferencing was "very useful," contrary to the widely held opinion that live video is an unnecessary frill that doesn't improve communication. Notably, all of the students claimed that the course changed the way they saw themselves and/or the world afterward.

Some ongoing research on project-based design education is described in section IV.B.

IV. RESEARCH QUESTIONS

There are a number of open research questions associated with teaching design thinking and with effectively implementing project-based design education. New assessment techniques are required because new skills are being taught. For one example, directing students to work in teams—and assigning grades to individual students that reflect their work as members of a team—is a decided contrast with the prevailing traditional engineering curriculum pedagogies that evaluate the performance of students acting solely as individuals. Thus, new approaches are needed to assess the underlying theme of design learning for both emerging paradigms of design thinking and new modalities of design pedagogy. The standard measures of assessment used in engineering (and other) curricula include such "objective" measures as enhanced student interest in engineering (which is partly demonstrated by increased retention), better student motivation in upper-division engineering courses, better performance in capstone design experiences, and improved employer satisfaction with employee performance. (It is interesting that the possible interest of graduate schools in graduates of particular programs does not seem to be on anyone's list of measures of design teaching.)

Design is both a mechanism for learning and in itself a learning process. Thus, the notion of *instrumenting* student design activities and student performance enables instructors to better understand students' integrative thinking skills and their design skills [148, 149]. The notion that the classroom could be a research laboratory for the scholarship of teaching was pioneered by Angelo and Cross [150]. Instrumenting the classroom provides formative feedback on student learning; it also affords the opportunity to do research on the effects of multiple variables in the learning process. Several methods and metrics have proven useful in both design research and in evaluating design learning. Most have been applied to engineering design classes and thus provide insight into methods for evaluating those classes and developing indicators of performance of their design teams. Atman and her colleagues have also studied the various processes used to teach design and have conducted a wide range of research in understanding the skills and knowledge associated with design activities, along with identifying effective educational practices [151–155].

The work described in sections II and III used two assessment approaches to study the efficacy of different pedagogies, that is, both traditional measures of outcomes and, more recently, the instrumented classroom as a laboratory. These sections of the paper have stated what is known, what has been achieved. The next question is "What remains to be done?" This question is decomposed and answered as follows.

A. What is Design Thinking?

The review presented in section II reflects design thinking as currently viewed by design researchers and design practitioners. However, that picture is evolving, in large part because design has emerged as a recognizable field of research that is supported by national funding agencies, e.g., the National Science Foundation (NSF) and the Defense Advanced Research Projects Agency (DARPA). It is expected that in the future there will be further development of representations or languages of design, such as pattern languages, shape grammars, and better representations of design functionality. There will be better models of learning, by both people and machines. It is important that design educators stay in close touch with design researchers[5] because the fruits of design research enable both better understanding and better articulation of what is involved in doing design. A better understanding of how people design will certainly inform design pedagogy (see Section IV.B below). The visibility and presence of design in the engineering curriculum has benefited from the fusion of four trends: increased industry interest in engineering education; the increased interest of academic administrators and many faculty members in improving retention and learning outcomes; the effect of ABET's new engineering accreditation standards (a study of which is underway [156, 157]); and the emergence of a vibrant and strong community of design researchers. The synergy between research in design practice and design teaching has greatly benefited both endeavors [158].

B. How Can PBL Be Made Better?

As popular and widely practiced as PBL has become, the research done on PBL does not appear to be extensive. There are still open research questions about PBL itself:

- What are the best proportions of problems, projects, teamwork, technology, and reality for a given state of student development? In other words, how *authentic* should PBL experiences be compared to industry design experiences? Some work has begun to emerge in this area [159], but the answers are not yet definitive.
- How do the proportions change with regard to the context of different engineering disciplines and institutional missions?
- How should multidisciplinary design-learning teams be managed?
- Can a pedagogic framework developed for co-located learning teams be distributed in time and place? If so, how?
- How can students be *authentically* evaluated and graded in design courses with regard to, for example,
  a. the quality of the design produced vs. the quality of the process demonstrated; and
  b. individual cognitive development vs. collective team development?

Much effort has been devoted to furthering the understanding of individual influences on team behavior. In particular, using psychometric methods for analyzing team behavior to form teams has been reported by some as apparently successful [87], while others have found no relationship between personality mixes and team success [98]. One explanation for these seemingly contradictory results may be that effective teams are able to develop strategies to compensate for a range of personality mixes if they are aware of the differences during the team forming stage. With this philosophy in mind, one pedagogical approach is to ask teams to share their individual MBTI scores as a means to discuss their predilections and preferences for communicating and operating in team settings. More insight may be gained by exploring the relationship between personality types and learning style preferences [160–162]. Clearly, further research is needed on applying psychometric measures to analyze team behavior and to form teams, and on furthering the understanding of the impact of individual diversity factors on team performance.

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[5] While many design researchers do teach design, it is unfortunate that design *researchers* and design *teachers* seem to attend different professional meetings. While there are efforts to get the two groups to talk more (e.g., the Mudd Design Workshops and newly-begun efforts of the Design Education Committee of ASME's Design Engineering Division), there need be more such forums for interaction.

C. An Experiment in Globally Distributed PBL

Faculty who question the efficacy of PBL often ask, "What have students have learned?" One recently initiated, ongoing experiment answers that question, based on the observation that global teams consistently do a better job of *documenting* their products and work processes than do co-located teams. This instrumented classroom is an ongoing graduate mechatronics course taught simultaneously at three geographically dispersed universities, with students working together on distributed design projects with corporate project sponsors. The hypothesis of the experiment is that compared with baseline measures (using a means detailed below):

- students will be measurably more *aware* of what was learned;
- students will be measurably better at *articulating* the connections between their design process activities and what was learned; and
- students will be measurably better at *defining* what they learned from product embodiment.

The hypothesis is best tested with global design teams because all normal means of communication within the teams are broken and technical means for rebuilding communication channels are easily instrumented. Equally important, it seems evident that an extra effort to commuinicate effectively will be required to accomplish anything. Of course, co-located teams face related problems.

A *folio-thinking* project [163], concerned with problems of fragmentation and the absence of meaning in many students' experience of higher education, has been undertaken by faculty and students at Stanford, the KTH-Stockholm, and the University of Uppsala (Sweden) to experiment with electronic learning portfolios as an antidote. They examined the issues in a variety of curricula and from the six perspectives of engineering education, teacher training, library science, media technology, clinical medicine, and writing and rhetoric. A new model of instruction and a variety of learning activities were deployed to support student portfolio creation and reflection, and associated best practices for technology use were also developed [164]. These folio-thinking activities and tools were designed to enhance students' self-awareness by enabling them to make their tacit knowledge explicit and visible to themselves, as well as for others. *Coached folio-thinking* (CoFT) [165] is an extension of folio-thinking that implements a triple-loop-learning framework that was derived from field ethnography observations during a study of product development in a major automotive manufacturing company [166]. A key observation of that study, which was intended to identify knowledge use and re-use in design, was the identification of a loop in which a "process expert" is assigned to coach—but not direct or manage—a design team's activity. From the perspective of PBL, a coach is informed enough to insert the measurement instrument appropriately, at the right time, to ensure that high-quality information is acquired in a meaningful context.

The utility of the electronic-portfolio technology tools used in these courses is being evaluated using a formal instrumentation framework [167] and an assessment protocol approximating that recommended by Olds [168]. The tools support course material presentation and the capture of learning experiences, including reflection and communication.

While it is premature to report findings, it is safe to say that the role of the coach, like that of the knowledge broker in Hargadon's studies [169], is particularly important in global design team scenarios. Further, that role is augmented by the maintenance of both individual and team learning portfolios. While the recently acquired data are still being analyzed, it can be provisionally reported that:

- learning awareness in the coached cohort is superior to that in the uncoached control group, as revealed in post-course interviews; and
- students in the coached cohort are better able to articulate what they have learned than those in the uncoached control group, as revealed in an epilogue section of the students' final reports.

D. How Can Students Learn Design Thinking More Effectively?

There are several open research questions on design pedagogy that have their roots in the review of design thinking. For example, how can effective inquiry, the systematic interplay between divergent and convergent questions, be taught and promoted as part of engineering education? One possible method is to use the question-centric thinking process described earlier as a tool for raising students' awareness of the effective inquiry process in design. However, the real challenge is not the adoption of the principles of divergent-convergent inquiry; rather, it is the integration of divergent-convergent inquiry into the existing engineering curricula:

- Can exam questions in an engineering science course be designed to require students to generate concepts by asking generative design questions and then to reason about them by asking deep reasoning questions before offering solutions?
- If such exams could be designed, how would their concept generation performance be graded, since concepts are neither true nor false?
- In a similar vein, how are students encouraged to fully assimilate and take ownership of the idea that design—and engineering generally—are expressed and applied in multiple languages? Is this an open research question, or is it also a question of explicit integration into engineering curricula?

It might also be asked whether it is possible to promote effective inquiry with the methods used to teach creativity in design classes, assuming that creativity can be taught and its increase can be measured? Although divergent inquiry can be considered to be a dimension of creativity, the answer to this question appears to be "No" because established creativity methods do not leverage inquiry; rather, they tend to promote divergent thinking only. However, there are clearly unanswered questions here about what defines creativity, how it can be measured, and how it relates to other characteristics of design thinking?

Case studies have long been used in engineering education to describe how analysis can be made useful in the real world, to describe various design endeavors, and to highlight industry's "best practices" [170, 171]. The case study method has been complemented and extended with the idea of artifact *dissection* in which students work in teams to take apart, "tinker, discuss, and reflect on engineered products." Also called *reverse engineering*, dissection can promote integrative thinking about design and also increase the retention and motivation of engineering students [120–122]. Dissection or reverse engineering has become extremely popular in engineering curricula today and researchers report that such courses not only improve retention, but also improve students' systems thinking of engineered products when integrated with other design or case study activities [122, 170–173]. The open questions here are about how far dissection can be taken to enhance student learning and about how much investment is required to provide the artifacts to be dissected, and the laboratory, shop, or studio facilities in which such case study and dissection activities can be undertaken. Further, how would such dissection exercises benefit from research advances in *case-based reasoning*, in which cognitive specialists try to derive models of human thinking based on how they learn to reason in cases they examine?

V. CONCLUSIONS AND RECOMMENDATIONS

This paper has discussed one major model of design pedagogy, project-based learning, as applied in two course contexts (i.e., first-year, and graduate, globally dispersed) and in several course variations (e.g., single projects, multi-project, case studies, dissection and design projects, etc.). In brief, available research suggests that these kinds of courses appear to improve retention, student satisfaction, diversity, and student learning.

On the other hand, it seems clear that the elements of these kinds of courses raise the costs of education (e.g., smaller sections, involvement of senior faculty), but, on a macro- or global scale, these costs are likely small compared to the cost of lost human talent in the engineering pipeline. In any event, no one has (yet) done the economic research needed to support or negate this assessment. Further, the metric of faculty involvement suggests that the long-term sustenance of cornerstone and other design courses might be problematic, regardless of how good the educational and retention results are [4]. This is clearly 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, and to create the facilities—such as design studios and associated shops—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.*

In addition, it should be said that there are ways of approaching design education that appear to offer both systematic payoffs and a framework for continuous quality enhancement. These methods include the following:

1. Imagine both engineering programs and their individual classes as potential laboratories in which pedagogical research can be conducted, while paying strict attention to the admonition that such research can—and must—be conducted in an ethical fashion that adheres to appropriate institutional "human subject" guidelines.
2. Instrument the curriculum-as-laboratory to obtain quantitative and qualitative data that support metrics consistent with quality control. This is invaluable in its own right and is consistent with what ABET is asking of engineering programs.
3. Embrace the notion that engineering design courses—and perhaps many other engineering courses—should be taught across geographically dispersed, culturally diverse, international networks.
4. Engage design coaches to help manage the contextualization of engineering design theory and practice. This would not only bring invaluable experience into design classrooms and studios, but would also help alleviate the shortage of faculty who want to teach design because they are comfortable with their own design experiences.
5. Challenge all engineering faculty to incorporate those habits of mind and the tools of design thinking into all parts of the engineering curriculum.
6. Define and study the cost of lost human design potential resulting from the lack of investment in design pedagogy.
7. Provide more forums where design practitioners, design teachers, design researchers, cognitive scientists, and experts on learning can come together to collaborate on all of the issues addressed above and more.

Finally, design education represents both serious challenges and glorious opportunities. Design is what engineers do, and the intelligent and thoughtful design of the engineering curriculum should be the community's first allegiance. An ideal outcome for all of the efforts discussed herein would be that every graduate of an engineering program resonates to a thought expressed by Albert Einstein and Theodore von Karman, among others, here paraphrased from words of the late Robert F. Kennedy [174]:

> *Scientists* see things as they are and ask, Why?
> *Engineers* see things as they could be and ask, Why not?

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