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Introduction

Engineering is being currently taught in the full spectrum of the P-12 system, with an emphasis on design-oriented teaching (Brophy, Klein, Portsmore, & Rogers, 2008). Due to only a small amount of research on the learning of engineering design in elementary and middle school settings, the community of practice lacks the necessary knowledge of the trajectory of students' learning progressions towards design mastery and expertise and the appropriateness of otherwise established design pedagogies. The issue is even more pressing since many states are embedding engineering into their standards without a clear notion of how engineering (often conceptualized as design) works within existing standards (Strobel, Carr, Martinez-Lopez & Bravo, 2011). This paper synthesizes existing literature, which might provide us with insights on how to further investigate the issue of appropriate design pedagogies. At first, the paper contextualizes existing PBL research into engineering design. Second, the paper synthesizes the literature on inductive teaching and expert-novice differences as an additional literature base to conceptualize the role of design and engineering in the schooling system. Third, the paper contextualizes the questions on problem-appropriateness in engineering design into the current debate on engineering standards and their role in the P-12 education system.

The PBL Argument

Engineering design challenges in the classroom expand on the traditional role of Problem-Based Learning (PBL), which is one of the best-researched instructional innovations. Across all age levels, PBL has been found to increase student motivation, performance on transfer tasks, deeper understanding of content particularly in the form of long-term retention (Strobel & van Barneveld, 2009), in addition to aiding in building mental models of difficult science and math concepts (Linn, diSessa, Pea, & Songer, 1994, Oliver & Hannafin, 2001). PBL particularly emphasizes problems characterized as *ill-structured* (Jonassen, 1997), *open-ended* (Prince & Felder, 2006) or *wicked* (Stoltermann, 2008).

Ill-structured problems are real-world problems, where multiple solutions and paths are possible, information might exist or may not be provided (Jonassen, 1997), and in which the learner must identify the goals, variables and strategies to solve them (Ertmer et al., 2009). Ill-structured problem solving resembles design problems and both can be multidisciplinary, requiring skills from multiple content areas or content specializations such as combining math and science or using skills from algebra and geometry. Well-structured problems, at the other end of the spectrum, are often used to practice information covered in a specific lesson or in assessing specific skills that are not context-dependent (Jonassen, 1997). Ill-structured and well-structured problems both have their places in education and "…they are not dichotomous. Rather they represent points on a continuum…." (Jonassen, 1997, p. 87). Research on professional engineers as they solved problems indicated that authentic problems are best understood as compound groups of intertwined well- and ill-structured problems (Strobel & Pan, in press).

Open-ended or ill-structured problems help to promote intellectual growth, which is needed by students entering into college-level engineering studies. College engineering students may have had less intellectual development than students from other majors, who may be more dependent on authority and unwilling to challenge what is accepted to move into higher levels of intellectual development as may be expected of scientists and engineers (Felder & Brent, 2004a).“Open-ended problems that do not have unique well-defined solutions pose serious challenges to students’ low-level beliefs in the certainty of knowledge and the role of instructors as providers of knowledge. Such challenges serve as precursors to intellectual growth” (Prince & Felder, 2006, p. 7). Our position in this paper is that the dichotomy of well- and ill-structured design may be resolved by looking at the intertwinedness of different and necessary competencies to solve complex problems.

Inductive learning providing insight for the pedagogical support

Theoretical constructs on inductive and deductive instruction or learning provide additional support for a more ill-structured problem solving approach in P-12 engineering. Deductive teaching, stating a principle and then moving to applications is the traditional way of teaching engineering (Prince & Felder, 2006). In inductive teaching, problems or applications are presented and students learn the theories as needed to find the solutions (Prince & Felder, 2006). Inquiry learning, problem-based learning, project-based learning and case-based teaching are examples of inductive teaching that are proposed for application in engineering education (Prince & Felder, 2006). Deductive learning not only fails to motivate students but also fails to build on existing knowledge (Felder & Brent, 2004a). Providing a problem to be solved that sets up the need for information or skills provides instant relevance to the learners. Inductive learning, active learning and cooperative learning increase motivation, knowledge retention and deeper understanding (Felder & Brent, 2004b).

While advocating inductive teaching, Prince and Felder (2006) promote the use of a cycle of inductive to deductive to inductive teaching that provides motivating applications or problems that lead students to need information and skills, which adds instant relevancy. While the instructor in student-centered learning takes on the role of challenger and knowledge facilitator, some traditional instruction can be used to provide the needed information. Further applications or problems can be posed which incorporate even new concepts with the new information in a blend of inductive and deductive teaching. Constructivist in nature, the careful sequencing allows students to stay within Vygotsky's "zone of proximal development" while taking advantage of Bruner's conceptualization of the spiral curriculum (Prince & Felder, 2006). The “zone of proximal development” refers to the difference between individual problem solving ability and the approach used when receiving guided instruction (Vygotsky & Cole, 1978). Bruner’s spiral curriculum allows a student to revisit previously learned concepts in order to support higher level or more sophisticated information (Bruner, 1977). "Material should not be presented in a manner that requires students to alter their cognitive models abruptly and drastically… students should not be forced outside their “zone of proximal development (Prince & Felder, 2006, p. 4)."

Expert-Novice Literature

Engineering design problems provide familiar and real-world contexts in which learners (Tate, Chandler, Fontenot, & Talkmitt, 2010) can apply science and math concepts and develop mastery or expertise in new competencies: The Five-Stage Model of Dreyfus and Dreyfus (1980) outlined a path from novice to expert built on the premise that concrete experiences, rather than abstract principles, are the key to reaching the expert stage. Dreyfus and Dreyfus did not discount the need for abstract principles or conceptual content knowledge, but note the dramatic increase in performance once meaningful contexts are applied. "We argue that skill in its minimal form is produced by following abstract formal rules, but that only experience with concrete cases can account for higher levels of performance (p. 5)." As something becomes familiar, it becomes automatic and performance continues to improve naturally while new information or skill levels are added (Schneider & Shiffrin, 1977). Open-ended learning environments, which include ill-structured design challenges, allow students the opportunities to move from immature or incorrect mental models towards those of experts (Oliver & Hannafin, 2001).

Ertmer et al., (2009) compared novices to experts in ill-structured instructional design problems, noting that novices do not recognize the ill-structured problem for what they are, and spend little time analyzing the problem or considering multiple solutions. Experts, on the other hand, analyze the problems in depth and apply information from past experiences and knowledge while finding greater depth in the problem (Ertmer et al., 2009). “Experts possess more highly developed problem schemas because they represent problems physically in terms of real world mechanisms” (Jonassen, 1997, p.79).

Not only is cognitive load reduced and expertise fostered, providing real-life relevance in problem solving is the most effective way to encourage intellectual development (Felder & Brent, 2004). Tasks which are appropriate for any level of engineering education should include: predicting outcomes, interpreting and modeling physical phenomena, generating ideas and brainstorming, identifying problems and troubleshooting, formulating procedures for solving complex problems, formulating problems, as well as making judgments and decisions and justifying them (Felder & Brent, 2004a, p. 5).

Integration of Engineering to Strengthen Academic Standards

Pre-collegiate engineering education, whether it be stand-alone or infused into other content, aids development of engineering “habits of mind,” which include “1) systems thinking, 2) creativity, 3) optimism, 4) collaboration, 5) communication, and 6) ethical considerations,” (Katehi, Pearson, & Feder, 2009, p.7) and are linked to essential 21st Century Skills that are related to all subject areas. Engineering design challenges work to meet expectations for instruction in 21st Century Skills by teaching students adaptability, complex communication, social skills, non-routine problem-solving, self management, and systems knowledge (Bybee 2009; Dym, Agogino, Eris, Frey, & Leifer, 2006). Engineering design promotes questioning and inquiry, which develop the ability to reason, particularly with math and science content (Dym et al., 2009). The first step in any design project involves asking questions to reveal the problem. Engineering promotes systems knowledge, which requires greater complexity from emerging engineers who need to deal with the dynamics of ever-expanding systems (Dym et al., 2009). Systematic thinking, reasoning, estimating and experimentation are beneficial habits of mind that will facilitate systems-focused engineers (Dym et al., 2009). Not only is problem-solving improved, but decision making is an important part of engineering education and engineering design (Dym et al., 2009). Collaborative teamwork in engineering helps learners to improve their decision making because they must learn to negotiate with group members, a process that requires internal sense making and decision making (Dym et al., 2009).

The importance of teaching engineering prior to the time students reach college is magnified by a 2008 study (Harris and Rogers) that examined competencies students should have before entering firstyear engineering courses. While "other-related competencies" were overall rated higher than some specific engineering, science, and math competencies, it is easy to see how integrated engineering instruction is important. Other-related competencies for incoming firstyear engineering students of importance are: 1) effective communication through writing; 2) reading comprehension; 3) honesty; 4) willingness to learn; 5) openness to new ideas; 6) problem solving skills; and 7) ability to follow directions (Harris & Rogers, 2008).

The habits of mind and 21st Century Skills that engineering can foster are reflected, for the most part, in those competencies (Bybee 2009; Dym, et al., 2005; Katehi et al., 2009). Important engineering/technology competencies for incoming first year engineering students include: 1) ability to sketch designs; 2) ability to operate fabrication equipment; 3) basic knowledge of engineering and the fields of engineering; and 4) ability to apply the engineering/technology design process. Mathematics competencies include: 1) competency in algebra; 2) competency in trigonometry; and 3) computation skills. Science competencies include: 1) ability to read meters, scales and other instruments; 2) relating science to math concepts; and 3) applying physics skills (Harris & Rogers, 2008). These findings highlight the importance of sequencing integrated engineering instruction in order to start building engineering capacity from an early age. Currently, there are states that have established engineering standards that allow for a sequential implementation of engineering knowledge and skills from first through twelfth grades that hopefully will help to prepare students to enter college with the competencies and intellect needed to become creative and expert engineers.

Existing state content standards and national technology standards help provide a model that is useful in building a logical sequence for learning engineering content (Strobel, Carr, Martinez-Lopez, & Bravo, 2011; Committee on Conceptual Framework for New Science Education Standards, 2010) that facilitates student preparedness for collegiate engineering education (Harris & Rogers, 2008) and learning progressions through different age and grade levels.

Integrating engineering at the secondary level (and all of P-12) is important because it meets the needs of schools that are looking for problem-based, hands-on and inquiry-related activities to integrate math and science content in a meaningful way (Carr & Strobel, 2011). Engineering, the "missing E," of STEM (science, technology, engineering and mathematics) allows for integration of design activities into curricula (Brophy et al., 2008). Engineering provides a meaningful context for applying math and science principles (Chae, Purzer, & Cardella, 2010) and leads to improvements in math, science and technological literacy (Chandler, Fontenot, & Tate, 2011).

Engineering design goes beyond the normal problem-solving process, as testing and improving are traditional mainstays of the engineering design process (Strobel, Carr, Martinez-Lopez, & Bravo, 2011). A derivation of engineering design challenges called model-eliciting activities (MEAs) also contribute to the framework. MEAs are a form of open-ended problems based in real-world engineering contexts where a process that can be generalized, or a model, is the end product (Diefes-Dux, Moore, Zawojewski, Imbrie, & Follman, 2005). The engineering design process is applied in a mathematical context where the solution is tested with new data and improvements are made (Diefes-Dux, et al., 2005). Both engineering design and MEAs are being taught at various levels, from elementary school to university (Chamberlin & Moon, 2005; Carr & Strobel, 2011), and provide an underutilized connection of engineering to existing academic standards, which are often exclusively science oriented (Brophy et al., 2008).

Conclusion

It is not just rhetoric to state that more research is needed in early design and engineering/design progressions in the P-12 system. Without the necessary research, appropriate needs assessment for building a model for the trajectory of engineering education throughout the grades is not possible and ultimately engineering in high school does not receive the appropriate foundation. From existing literature in a variety of contexts, a case can certainly be made that ill-structured problems have the greatest promise not only for the development of complex competency and transfer, but for the learning of the basics as well. This paper argues for resolving the dichotomy of ill-structured vs. well-structured problems by focusing on the intertwinedness of ill- and well-structured problems in authentic real world contexts; utilizing models of deductive teaching and expertise development as support for competency development; and integrating engineering into the existing standards, particularly where less integration appears, as in the case of mathematics.

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