AC 2008-2738: CHARACTERIZING COMPUTATIONAL ADAPTIVE EXPERTISE

Ann McKenna, Northwestern University

Ann McKenna is the Director of Education Improvement in the Robert R. McCormick School of Engineering and Applied Science at Northwestern University. She holds a joint appointment as Assistant Professor in the School of Education and Social Policy and Research Assistant Professor in the Department of Mechanical Engineering. She also serves as Co-Director of the Northwestern Center for Engineering Education Research (NCEER). Dr. McKenna's research focuses on the role of adaptive expertise in engineering education, design teaching and learning, and teaching approaches of engineering faculty. Dr. McKenna received her B.S. and M.S. degrees in Mechanical Engineering from Drexel University and Ph.D. in Engineering, Science and Mathematics Education from the University of California at Berkeley.

Robert Linsenmeier, Northwestern University

Robert A. Linsenmeier has a joint appointment in Biomedical Engineering in the Robert R. McCormick School of Engineering and Applied Science, and in Neurobiology and Physiology in the Weinberg College of Arts and Sciences. He is the Associate Director of the VaNTH Engineering Research Center in Bioengineering Educational Technologies, former chair of the Biomedical Engineering Department at Northwestern, and a fellow of the American Institute of Medical and Biological Engineering and the Biomedical Engineering Society. His research interests are in the role of retinal oxygen transport and metabolism in both normal physiological conditions and disease, and in bioengineering and physiology education.

Matthew Glucksberg, Northwestern University

Characterizing Computational Adaptive Expertise

Abstract

Our research is exploring the role that computational and analytical abilities play in innovation, in the context of engineering design education. We are applying the learning framework of adaptive expertise to focus our work and guide the research. The model of adaptive expertise has been presented as a way of thinking about how to prepare learners to flexibly respond to new learning situations, which is precisely what students are expected to do in the context of developing design solutions. We focus on "computational adaptive expertise," which we abbreviate CADEX, since a major portion of an engineering curriculum focuses on developing analytical and computational knowledge. Yet, students often struggle with applying or transferring computational knowledge in the context of design. The current paper presents an overview of adaptive expertise and relates this concept specifically to engineering design education. In addition, the paper presents an overview of the research plan we are presently using to study CADEX in the context of a senior level biomedical engineering design course.

Introduction

Several recent reports stress that the competitive advantage of the U.S. lies in its role as a leader in technological innovation[1,2]. These reports make statements such as "leadership in innovation is essential to U.S. prosperity and security"[3] and "innovation will be the single most important factor in determining America's success through the 21st century"[1]. These reports send a resounding message that engineering education in the U.S. needs to emphasize and develop knowledge and skills that are essential to innovation in a rapidly evolving technological society. From an education standpoint, there are many factors to consider in creating an environment that fosters and develops the ability to engage in technological innovation. For example, students need to develop cognitive abilities such as technical fluency in a domain, as well as the ability to approach problems from a multidisciplinary perspective.

Our study is investigating the role that computational and analytical abilities play in innovation in the context of a conceptual framework that has recently emerged in the engineering education literature: adaptive expertise. The model of adaptive expertise has been presented as a way of thinking about how to prepare learners to flexibly respond to new learning situations. The current conception is that developing adaptive expertise requires development along two axes: innovation and efficiency[4]. Specifically, we are studying adaptive expertise as it applies to how one flexibly uses computational knowledge in novel situations.

We focus on "computational adaptive expertise," which we abbreviate CADEX, since a major portion of an engineering curriculum focuses on developing analytical and computational knowledge in specific disciplinary domains. However, many engineering courses teach these topics "in the abstract," and place less emphasis on how to adaptively use computational knowledge. That is, historically engineering curricula have been based largely on an "engineering science" model where engineering is taught only after a solid basis in mathematics and science[5,6]. Furthermore, engineering courses often focus on reductive thinking and "require

students to learn in unconnected pieces, separate courses whose relationship to each other and to the engineering process are not explained until later in a baccalaureate education, if ever"[7] (p. 5).

As a first step in the research we are focused on characterizing the nature of CADEX and describing this concept in the context of previous work on adaptive expertise. Specifically, we aim to understand the type of computational knowledge that is required to develop innovative and effective solutions to design problems. We claim that this is a necessary first step in our research, which has an overarching aim to develop instructional strategies that foster the development of CADEX. That is, in simple terms, we want to identify what we are looking for before trying to measure and evaluate it.

This paper addresses our "first step." Specifically, we provide an overview of the concept of adaptive expertise and relate the framework to engineering design education. This helps situate our work within the broader scholarship on the topics of expertise, problem solving, and innovation. Through the literature review we have also identified methods that have been effective in measuring attributes of efficiency and innovation, which we have since modified for our study. The paper also presents details on how we have modified various methods for a study we are currently conducting in the context of a senior level biomedical engineering design course.

Theoretical Framework of Adaptive Expertise

Schwartz, Bransford, and Sears[4] proposed that adaptive expertise emerges from a balance between efficient use of knowledge and the innovation skills associated with accessing prior knowledge, and generating new ideas and new knowledge. This relationship is represented in Figure 1. The efficiency scale (x-axis) indicates an individual's competence to fluently apply knowledge and skills to complete activities they have significant experience performing. Their ability to replicate their performance within various contexts improves as they gain more experience. Novices can accurately perform on only a small set of problems, so they are on the lower end of the scale. Experts have a wider range of experience and therefore solve a larger class of problems quickly and accurately.
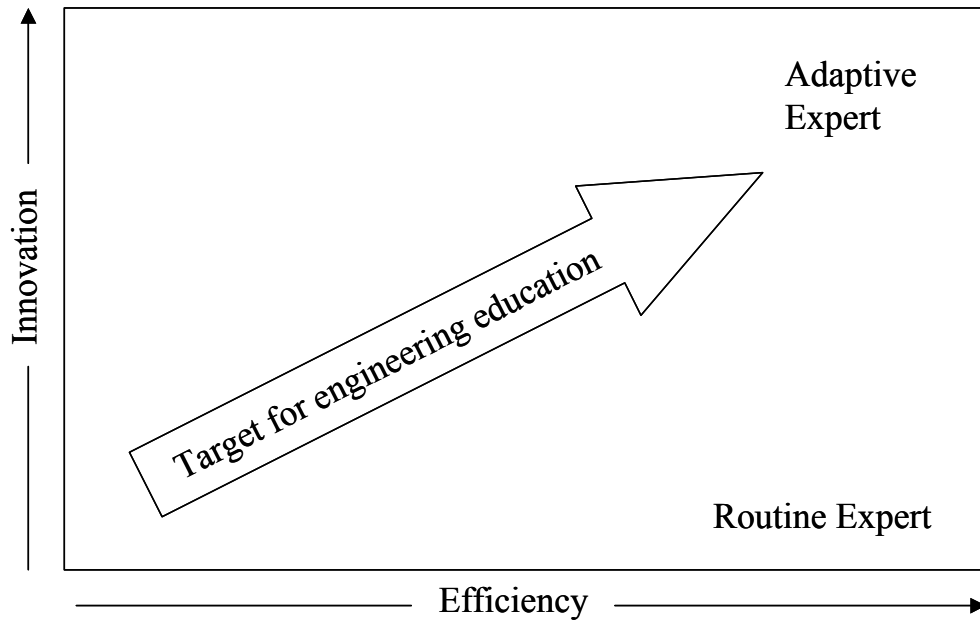
Figure 1: Adaptive expertise as a balance between two dimensions for learning and assessment: efficiency and innovation.

The innovation scale (y-axis) indicates a process of generating new knowledge and ideas that are useful for achieving a novel and appropriate goal. New knowledge can improve on old ideas or identify completely new directions for approaching one's goal. Therefore, part of the innovation axis relates to inquiry and self-regulating skills necessary to identify and comprehend a problem, identify what additional knowledge is necessary, and generate ideas and leverage existing knowledge to facilitate noticing of relevant information. Therefore, the innovation scale relates to the skills used to apply the knowledge along the efficiency scale to support the generation of new knowledge. It seems clear that computational facility plays a role in increased efficiency, but we suggest that it plays a role in innovation as well. We hypothesize that one of these innovation elements is the application of computational strategies. Briefly, these allow the engineer to represent vague problems in a tractable way and to gain some understanding of whether each potential solution has merit with less investment in trial and error.

Situating Computational Adaptive Expertise in Engineering Design

We claim that in order to study adaptive expertise in general, and CADEX in particular, one must situate the research in a setting that allows, in fact requires and rewards, learners to use knowledge in novel ways, i.e. to be innovative. In an engineering curriculum the most natural place for this type of innovative activity is in design courses. Therefore, we are investigating CADEX in the context of engineering design.

Design represents a particular class of problem solving that is distinguished by ambiguity, the existence of multiple solutions (as well as multiple problem representations), and a lack of procedural and declarative rules[8,9]. Design is situated in real contexts, involves social processes,[10] and involves people with different perspectives (designers, non-designers, users,

etc.) from different disciplines (within and outside of engineering) working together to solve complex technological problems that address societal as well as consumer needs.

Situating CADEX within Current Literature on Adaptive Expertise

Many studies have been conducted to study differences between experts and novices. For example, the literature reports that experts 1) solve problems faster and more accurately than novices,[11] 2) have well-organized knowledge structures,[12] and 3) notice meaningful patterns of information and can flexibly retrieve important aspects of their knowledge with little attentional effort[13]. The expert-novice studies have led educators to a more formal understanding of the differences in problem solving approaches and cognitive abilities between experts and novices in a variety of domains[14,15,16].

The concept of adaptive expertise was introduced to extend our understanding of the meaning of expertise. Hatano and Inagaki[17] contrasted two types of expertise: routine and adaptive. They claim, "routine experts are outstanding in speed, accuracy, and automaticity of performance but lack flexibility and adaptability to new problems"[17](p. 266). Furthermore, Hatano and Oura[18] explained that the majority of studies on expertise "have shown that experts, who have had many years of problem-solving experiences in a given domain, can solve familiar types of problems quickly and accurately, but often fail to go beyond procedural efficiency"[18](p. 28). In contrast, adaptive experts can go beyond procedural efficiency and "can be characterized by their flexibility, innovative, and creative competencies within the domain"[18] (p. 28).

Furthermore, the concept of adaptive expertise grew out of research focused on how individuals transfer knowledge among different learning activities, to allow for solutions to new problems. Transfer studies often produce disappointing results because, as Bransford and Schwartz[19] argue, they occur in settings that do not allow for testing new ideas and revising as necessary, and transfer studies too narrowly focus on measuring "replicative" (or procedural) knowledge. That is, traditional approaches to study transfer did not focus on capturing the types of knowledge individuals are capable of transferring in to new situations, or on the types of resource that better prepare students for subsequent learning. Schwartz et al. state: "for many new situations, people do not have sufficient memories, schemas, or procedures to solve a problem, but they do have interpretations that shape how they begin to make sense of the situation"[4](p. 9). That is, how one interprets new situations and how one frames a problem "has major effects on subsequent thinking and cognitive processing"[4] (p. 9). The focus on transfer and more specifically on the type of knowledge that gets transferred into and out of situations sets the stage for research on the concept of adaptive expertise[20].

The concept of adaptive expertise presents an interesting challenge to the education community. That is, if we agree that it is important for learners to develop adaptive expertise, then how might we define its meaning for particular disciplines, and also how might we provide instructional experiences to develop it? Our research is focused on the computational expertise that gets transferred into and out of innovative design tasks, as well as on investigating instructional strategies that enable learners to fluently develop these skills.

A few studies have been done within engineering education to explore the concept of adaptive expertise. Pandy et al.[21] used the How People Learn (HPL) framework[4] and STAR-Legacy cycle[22] to develop instructional materials that focus on the development of adaptive expertise in biomechanics. In order to quantify adaptive expertise they introduced a weighted formula that includes factual knowledge, conceptual knowledge, and transfer. The rubric used for scoring responses included specific problem solving techniques such as writing equations, drawing a diagram, and correctly identifying variables. Their findings indicated that HPL approaches to instruction increased students' conceptual knowledge and ability to transfer knowledge, as defined by the rubric.

Walker et al.[23] investigated the concept of adaptive expertise in the context of an introductory engineering science course and a senior design course in biomedical engineering. They used a design scenario approach[24] to evaluate students' responses to an open-ended problem. Based on students' responses they evaluated the quality of strategies, the quality of students' questions, and confidence. Furthermore, they categorized the quality of strategies as the efficiency dimension of adaptive expertise and the quality of students' questions as the innovation dimension. Their findings suggest that fourth-year students devised more efficient and innovative solutions than first-year students and over time all students became more confident.

More recently, Neeley has built on Schwartz and Bransford's work, and developed a theory of adaptive design expertise that incorporates active, abstractive and adaptive dimensions that further articulate exactly what sort of design competencies are being employed at various levels of design expertise[25]. The active dimension consists of three progressively more sophisticated design activities: re-use of existing designs, altering existing designs, or creating new designs. The abstractive dimension consists of three progressively more sophisticated levels of intellectual development: thinking in terms of the designed product, the design process, or the design paradigm itself. The adaptive dimension, in this model, is the third dimension which represents the ability to know when to design and/or think at any of the points along the other dimensions. Neeley explains, "If we consider the first two dimensions as describing a design thinking toolset, the adaptive dimension characterizes the designer's ability to align tool with task"[25] (pp.66-67). Neeley goes on to explain that the adaptive dimension means being neither committed to the same design tools that have served in the past regardless of the needs of a design problem, nor being "preoccup[ied] with creating the new"(p.67).

While these studies have shown promising findings with respect to developing aspects of adaptive expertise within engineering, our research focuses specifically on characterizing the nature of the transfer (or lack thereof) of computational engineering knowledge into students' design process. The current research investigates a specific aspect of adaptive expertise (CADEX), in the context of a particular discipline (engineering design), and includes multiple perspectives from academia and industry.

Characterizing CADEX and our Research

Currently we take a broad view of "computational knowledge." Specifically, we do not mean just the mechanics of calculation. Rather, CADEX likely also encompasses approaches to problem formulation, estimation, and strategies for translating the physical world into models appropriate

for engineering analysis in the context of design. To explore the nature of CADEX, our current work is investigating the following research questions:

- What is the nature of computational knowledge students bring to bear when developing design solutions?
- What is the nature of computational knowledge that faculty (or experts) consider to be important for students to utilize when developing design solutions?

In this section we present our general approach to explore the two questions provided above. Since we are trying to characterize the phenomenon that is under investigation, namely CADEX, the first phase of our research is exploratory in nature. That is, the goal is to ask both students and faculty about the nature of the computational knowledge that is important when developing design solutions. From this information we can obtain expert and novice perspectives (faculty and student, respectively) on our concept of CADEX.

Our first round of data collection is taking place in a required senior-level design course in biomedical engineering (BME). The course is being offered this winter quarter 2008 and, as is usually the case has an enrollment of approximately 70 students. Drawing on previous studies related to adaptive expertise we developed an approach that serves as a pedagogical tool as well as an assessment method for our research. Specifically, Schwartz and Martin[26] describe an approach called "inventing to prepare for future learning" (IPL). In IPL, students engage in "invention" activities in which they are asked to invent procedures or models of a particular concept, theory, mathematical formula, etc. The premise of IPL is that the "value of invention activities is that they prepare students to learn" from more traditional direct instruction approaches such as lectures[26] (p. 144).

Schwartz and Martin[26] created what they call "invention-presentation couplets" that pair an invention activity to a direct instruction and practice presentation afterwards. For example, for an invention activity, prior to any formal instruction on the topic, Schwartz and Martin gave students different data sets about sports statistics and asked them to invent a procedure for comparing the data to determine "who has the best high jump record." The invention activity was then followed by an instruction and practice exercise where the instructor displayed the mean deviation formula and described how it operated over small data sets.

From a pedagogical point of view, the BME design course has several educational goals that align directly with our CADEX research, and that are suited to the IPL approach. Specifically, a primary course objective is to have students apply their knowledge of engineering and biological sciences to product design. Most engineering design courses have a similar objective, however, the instructors and authors have noted (based on over 25 years of combined design teaching experience) that students often have difficulty recognizing when particular disciplinary knowledge applies, and struggle with some of the more sophisticated computational decisions that arise when developing solutions. To address these issues we have created a classroom and assessment activity modeled after the IPL approach. The overarching pedagogical goal is to better prepare students to apply computational (or disciplinary) knowledge as appropriate for their particular design project.

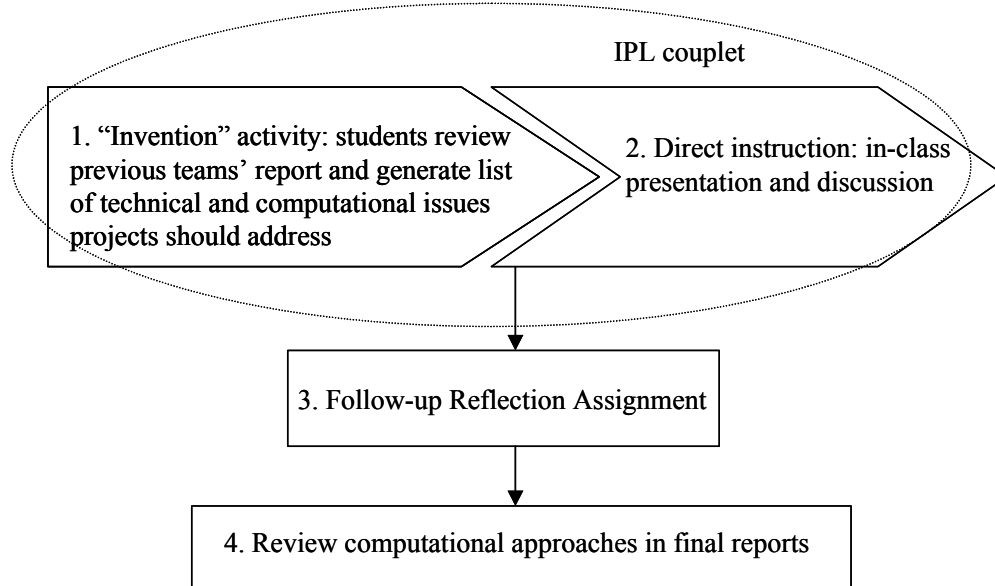The method, including instruction and assessment, that we have designed is shown in Figure 2.

Figure 2. Schematic of the instruction and assessment in BME design class.

Details about each of the numbered steps are provided below.

1) The invention activity is given as a homework assignment. Students are asked to review a previous team's report with a critical eye regarding the technical/computational components of the team's work. The homework includes two invention activities. In the first, students are asked to generate a list of the technical details that all design projects (and reports) should include. In the second, students are asked to generate the factors that would make a design solution "innovative." We also ask these same questions to faculty in order to obtain an expert perspective for comparison purposes.

2) Based on the IPL approach, these invention activities should better prepare students to benefit from the in-class discussion. During the class the instructor leads a discussion about the previous team's report, focusing on the computational aspects of the design. The instructor presents his perspective on the essential computational features design solutions should address, and in this way is providing direct instruction related to the invention activity.

3) Students are asked to complete the same invention questions a second time in order to determine if their perspective has evolved based on the IPL couplet instructional approach. In addition, student responses are compared to faculty responses to determine if there is movement from a novice to expert perspective.

4) Student reports will be analyzed with respect to the computational details included in their designs. This helps us to determine if the knowledge from the IPL couplet gets transferred to students' actual design project work.

As previously described, the method outlined in Figure 2 serves as an instructional approach to help us better prepare students to raise the level of the computational and disciplinary knowledge

used in their design solutions. However, in addition, this approach enables us to collect critical data to inform our research regarding the nature of CADEX, and how this gets operationalized in the context of engineering design.

Even though we have designed our data collection to include pre and post measures, given that this part of the research is exploratory in nature, we are not focused on measuring cause-and-effect outcomes. That is, this method is not designed to prove that the IPL method "works." Rather, this method allows us to collect data needed to better characterize CADEX, and allows us to draw comparisons 1) between faculty and students' perspectives of CADEX and 2) about the evolution of students' perspective on CADEX over time. Furthermore, the method in Figure 2 satisfies an instructional need of the course such that it presents a theoretically-grounded pedagogical approach for helping students develop a more sophisticated understanding of the technical and computational knowledge that is useful (and necessary) in design innovation. Finally, by examining students' actual work product, in this case their final reports, we can determine the types of computational knowledge that gets transferred into their design solutions, and what does not.

Discussion and Future Work

The goal of this paper was to present an overview of the framework of adaptive expertise and to relate this framework to our research regarding CADEX. The framework of adaptive expertise holds promise for studying CADEX since it serves as a way of thinking about how to prepare learners to flexibly respond to new learning situations, which is precisely what students are expected to do in the context of developing design solutions. Our research focuses on "computational adaptive expertise," since a major portion of an engineering curriculum focuses on developing analytical and computational knowledge. Yet, students often struggle with applying or transferring this knowledge in the context of design. The current paper laid the groundwork for studying this important concept and also presented a theoretically grounded approach for instruction and assessment. We are currently applying this method to study CADEX in the context of a senior level biomedical engineering design course. Future work will present findings from this study and expand upon the computational nature of developing effective and innovative design solutions.

References

1. Council on Competitiveness (2005). Innovate America: National innovation initiative summit and report, www.compete.org.

2. Task Force on the Future of American Innovation (2005). The Knowledge Economy: Is the United States Losing It's Competitive Edge?, www.futureofinnovation.org

3. Committee to Assess the Capacity of the U.S. Engineering Research Enterprise (2005). Engineering Research and America's Future: Meeting the Challenges of a Global Economy, Washington, DC: National Academy of Engineering.

4. Schwartz, D.L., Bransford, J.D., and Sears, D. (2005). "Efficiency and Innovation in Transfer," In Jose Mestre, Transfer Of Learning: Research and Perspectives, Information Age Publishing Inc., 1-51.

5. Dym, Clive L., Agogino, Alice M., Eris, Ozgur, Frey, Daniel D. and Leifer, Larry (2005). Engineering design thinking, teaching, and learning, Journal of Engineering Education, 94 (1), 103-120.

6. Dym, Clive L. (2004). Design, systems, and engineering education, International Journal of Engineering Education, 20 (3), 305-312.

7. Bordogna, Joseph, Fromm, Eli, and Ernst, Edward W. (1993). Engineering education: Innovation through integration, Journal of Engineering Education, 82 (1), 3-8.

8. Jonassen, D., Strobel, J. & Beng Lee, C. (2006). Everyday Problem Solving in Engineering: Lessons for Engineering Education. Journal of Engineering Education, 95(20), 139-151.

9. Goel, V. and Pirolli, P. (1992). The Structure of Design Problem Spaces. Cognitive Science, 16, 395-429.

10. Bucciarelli, L. L. (1996). Designing engineers. Cambridge: MIT Press.

11. Larkin, Jill, McDermott, John, Simon, Dorothea, P. and Simon, Herbert A. (1980). Expert and Novice Performance in Solving Physics Problems, Science, 208 (4450), 1335-1342.

12. Bruer, John, T. (1993). Schools for Thought: A science of learning in the classroom, Cambridge MA: The MIT Press.

13. Bransford, J. D., Brown, A. L., and Cocking, R. R. (Eds.) (2000). How People Learn: Brain, Mind, Experience, and School, Washington, DC: National Academy Press.

14. Chi, M, Feltovich, P. & Glaser, P. (1981). Categorization and Representation of Physics Problems by Experts and Novices, Cognitive Science, 5 (2), 121-152.

15. Scardamalia, Marlene and Bereiter, Carl (1991). Literate Expertise. In K. Anders Ericsson and Jacqui Smith (Eds.), Toward a General Theory of Expertise: Prospects and Limitations, New York, NY: Cambridge University Press.

16. Patel, Vmila, L. and Groen, Guy, J. (1991). The general and specific nature of medical expertise. In K. Anders Ericsson and Jacqui Smith (Eds.), Toward a General Theory of Expertise: Prospects and Limitations, New York, NY: Cambridge University Press.

17. Hatano, G., and Inagaki, K. (1986). Two Courses of Expertise, In H. Stevenson, H. Azuma, & K. Hakuta (Eds.), Child development and education in Japan, New York: Freeman, 262–272.

18. Hatano, G., and Oura, Y. (2003). Commentary: Reconceptualizing School Learning Using Insight From Expertise Research, Educational Researcher, 32(8), 26–29.

19. Bransford, John D. and Schwartz, Daniel L. (1999). Rethinking transfer: A simple proposal with multiple implications, Review of research in education, vol. 24, 61-100.

20. McKenna, Ann F. (2007). An Investigation of Adaptive Expertise and Transfer of Design Process Knowledge, 129 (7), July 2007, ASME Journal of Mechanical Design, pp. 730-734.

21. Pandy, M.G., Petrosino, A.J., Austin, B. and Barr, R. (2004). Assessing Adaptive Expertise in Undergraduate Biomechanics, Journal of Engineering Education, 93, 211-222.

22. Schwartz, D. L., Lin, X., Brophy, S., & Bransford, J. D. (1999). Toward the development of flexibly adaptive instructional designs. In Charles M. Reigeluth (Ed.) Instructional Design Theories and Models, Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

23. Walker, Joan M.T., Cordray, David S., King, Paul H., and Brophy, Sean P. (2006). Design scenarios as an assessment of adaptive expertise, International Journal of Engineering Education, 22 (3), 645-651.

24. McMartin, F., McKenna, A., and Youseffi, K. (2000). Scenario Assignments as Assessment Tools for Undergraduate Engineering Education, IEEE Transactions on Education, 43(2), 111-119.

25. Neeley, W.L. (2007). Adaptive Design Expertise: A Theory of Design Thinking and Innovation, Unpublished doctoral dissertation, Department of Mechanical Engineering, Stanford University.

26. Schwartz, Daniel L. and Martin, Taylor (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction, Cognition and Instruction, 22(2), 129-184.