Proceedings of IDETC/CIE 2006
ASME 2006 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conference
September 10-13, 2006, Philadelphia, Pennsylvania, USA

DETC2006-99711

EXPLORING ADAPTIVE EXPERTISE AS A TARGET FOR ENGINEERING DESIGN EDUCATION

Ann F. McKenna
Northwestern University
2133 Sheridan Road
Evanston, IL 60208
mckenna@northwestern.edu

J. Edward Colgate
Northwestern University
2145 Sheridan Road
Evanston, IL 60208
colgate@northwestern.edu

Gregory B. Olson
Northwestern University
2145 Sheridan Road
Evanston, IL 60208
g-olson@northwestern.edu

Stephen H. Carr
Northwestern University
2145 Sheridan Road
Evanston, IL 60208
s-carr@northwestern.edu

ABSTRACT
In this paper we present the concept of adaptive expertise and relate this concept to the design curriculum offered by the Institute for Design Engineering and Applications (IDEA) at Northwestern University. The model of adaptive expertise suggests that instruction and assessment include a balance of "efficiency" and "innovation". These two dimensions are first described from a theoretical perspective, then are discussed in more concrete terms in the context of the design experiences provided in IDEA. The model of adaptive expertise suggests that by providing learning experiences that balance these two dimensions we better prepare students to flexibly apply their knowledge in innovative ways. Since these aims are so closely aligned with the goals of design, we offer adaptive expertise as the target for engineering design education.

INTRODUCTION
Several education researchers have recently proposed a model for characterizing the attributes associated with "adaptive expertise" [1-5]. The concept of adaptive expertise suggests that the educational experience should have a balance of gaining technical proficiency with opportunities for applying one's knowledge in innovative ways. Ultimately the adaptive expert is someone who can flexibly apply deep content knowledge to invent innovative solutions to real needs.

The concept of adaptive expertise holds promise for engineering education, in particular as it relates to design education. Design courses emphasize learning-by-doing and applying knowledge and skills to develop feasible solutions to society's needs. Students are expected to apply rigorous design process principles as well as utilize domain specific knowledge to generate, analyze, and evaluate potential solutions. In addition, design requires a level of discipline, perseverance, and astute judgment. Design thinking, therefore, entails deep disciplinary and process knowledge as well as affective factors that impact one's motivation and persistence for working through the details of a complex problem.

In this way, design education appears to align nicely with the concept of adaptive expertise. In this paper we present the concept of adaptive expertise and describe how the design curriculum offered by the Institute for Design Engineering and Applications (IDEA) at Northwestern University aims to foster the development of adaptive expertise.

THEORETICAL FRAMEWORK OF ADAPTIVE EXPERTISE
The concept of adaptive expertise grew out of research focused on how individuals transfer knowledge among different learning activities. Schwartz, Bransford, and Sears present several novel perspectives for thinking about how one might successfully transfer knowledge learned in one situation to directly apply in new settings [1]. Transfer studies often produce disappointing results because, as Bransford et al. 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.

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" [1, p. 9]. That is, how one interprets new situations and how one frames a problem "has major effects on subsequent thinking and cognitive processing" [1, 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 the concept of adaptive expertise.

In order to frame the concept of adaptive expertise Hatano and Inagaki contrast two types of expertise: routine and adaptive [2]. They claim that "routine experts are outstanding in speed, accuracy, and automaticity of performance but lack flexibility and adaptability to new problems" [2, p. 266]. Furthermore, Hatano and Oura explain 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” [3, p. 28].

In contrast, an adaptive expert is one who can go beyond procedural efficiency and “can be characterized by their flexibility, innovative, and creative competencies within the domain” [3, p. 28]. The concept of adaptive expertise presents an interesting challenge to the education community. Specifically, if we recognize that the characteristics of adaptive expertise are desired attributes, how might we structure a learning environment to help one develop these characteristics?

In order to help address this question Schwartz et al. present a model for thinking about the benefits of combining instruction to focus on elements of routine and adaptive expertise. Figure 1 [1] presents two dimensions of learning in instruction and assessment: innovation and efficiency. Those who are high in efficiency can rapidly retrieve and effectively apply appropriate knowledge and skills to solve a problem. One example they provide of a routine expert is a doctor who frequently performs a particular type of surgery. Form an efficiency perspective, she can diagnose and treat a new patient quickly and effectively.

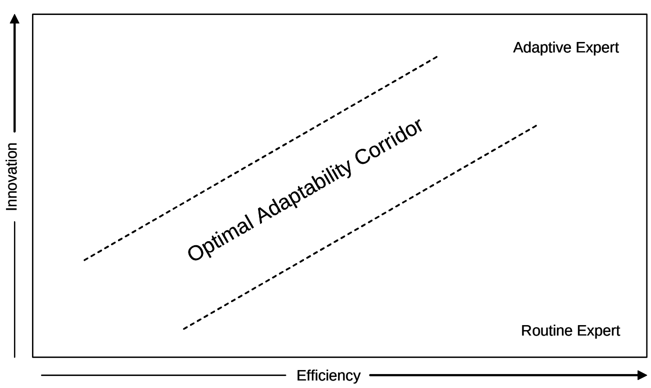

Figure 1: Adaptive expertise as a balance between two dimensions for learning and assessment: efficiency and innovation.

In contrast, the innovation scale represents a willingness to move away from being efficient and to challenge the status quo. The willingness to resist making assumptions in order to think deeply and creatively about a problem or situation is a characteristic associated with innovation. For example, Schwartz et al. describe the skilled musician who needed break free of well-learned routines so he could move to a new level of playing ability [1].

For those of us focused on designing instruction we are faced with the challenge of how to balance efficiency and innovation in the academic environment. Arguably, traditional engineering education has focused almost exclusively on the efficiency scale. As an alternative, adaptive expertise provides a useful way of framing the target for engineering education, in particular design education.

We revisit Fig. 1 to discuss what Schwartz et al. have termed an “optimal adaptability corridor” (OAC). The function of the OAC is to ensure that innovation and efficiency develop together [1]. We acknowledge the value of the OAC for reminding educators of the importance of these two dimensions and as a framework for gauging our instructional experiences. However, as other researchers have noted, we emphasize that there are possibly many different trajectories one might take to navigate to the goal of reaching adaptive expertise. Specifically, we do not intend to indicate that the path is linear or proceeds at steady pace (as could be interpreted by the roughly 45 degree path in Figure 1). Open questions remain about how to balance the two dimensions when providing instruction. Furthermore, it is unclear to what extent students regress and advance as they move along to path to adaptive expertise.

The following sections provide an overview of our design curriculum in IDEA and discuss aspects of our approach to design education that aims to foster the development of adaptive expertise.

INTERDISCIPLINARY DESIGN IN THE INSTITUTE FOR DESIGN ENGINEERING AND APPLICATIONS

At Northwestern University we established the Institute for Design Engineering and Applications (IDEA) within the engineering school to integrate interdisciplinary design throughout the curriculum. IDEA offers several design courses where students work in teams to develop design solutions to real projects for actual clients. Students interact with clients, product users, experts, instructors, and teammates throughout the design process and are required to convey design ideas to multiple audiences [6, 7].

We follow a collaborative and iterative process such that our curriculum conveys that the design process:

- is needs-driven (in contrast to specification-driven or hypothesis-driven).
- is about converting intellectual capital into products and processes that meet societal needs.
- encompasses many phases, and we provide students experiences from design conception to production.

The design projects we offer in IDEA fall into three basic categories: faculty-initiated, student-initiated, and client-initiated. Examples of each of these categories of projects are given in Table 1.

Table 1: Examples of design projects underway in IDEA.

Project Type	Project Name	Goal of Project	Relevance of Project
Faculty-Initiated	<u>Infant Feeder for HIV+ Mothers</u>	Design a milk feeding apparatus that will allow a	Every year, 219,000 new infections result from

		mother to safely and discreetly feed her child.	mother-to-child-transmission of HIV in sub-Saharan Africa. The design has the potential to have significant impact on decreasing the HIV infection rate [8].
Client-Initiated	NUberwalker	Design a treadmill/body weight support system for in-home use that enables stroke or spinal cord patients to regain normal gait patterns.	In the United States, there are 23,000 people with spinal chord injuries, 4 million have survived a stroke or brain attack and still living with after effects, 350,000 with multiple sclerosis, and 1.5 million with Parkinson's disease. The design would provide in-home therapy to a significant population of users [9].
Student-Initiated	NUSolar	Solar Car Team is an undergraduate student organization whose mission is to design, build, and race solar-powered vehicles for competition in the American Solar Challenge and Formula Sun races.	Enables students to apply engineering skills to design, build, test, and race a competitive next generation solar-powered vehicle against several other engineering schools.

Consistent with the concept of adaptive expertise we have embedded specific aspects of innovation and efficiency into our design experiences. The following two sections describe how we integrate aspects of these dimensions into our curriculum.

The Efficiency Dimension of IDEA

One way to operationalize efficiency is to describe it as knowledge or skills associated with completing a particular task. In the case of design, efficiency would entail design process knowledge such as generate alternatives, mockup ideas early to test and get feedback, understand the users, and perform research such as user observations. In addition, once a solution moves into the "detail design" phase (or even during the conceptual phase) then disciplinary knowledge comes to bear in order to perform appropriate engineering analysis, testing, modeling, and simulation.

All IDEA design projects require both design process and disciplinary knowledge in order to bring potential ideas to feasible solutions. The IDEA design curriculum, therefore, emphasizes the efficiency dimension of adaptive expertise by providing multiple opportunities for students to apply and reflect on their knowledge. The iterative cycle of our curriculum, as well as the iterative nature of design, in combination with the students' reflective activities, reinforces student learning. Borrowing from Schon's notion of "educating the reflective practitioner" [10], we require students to continuously ask and report back on reflective questions such as "what is the problem I am trying to solve?", "is my progress moving me towards a feasible solution?", and "what else should I be doing to help meet my design goals?"

The issue of transfer arises in design as an ongoing basis. Design process knowledge would "transfer in" as one is presented with a design challenge. That is, in order to get started on a good solution path it would be beneficial to have a "design process schema" as a mental model a priori. However, because design is an iterative process, there are elements of "transferring out" as one engages in developing a solution. For example, a student design team might brainstorm ideas, build mock-ups, and test different ideas with users. Once the team has some initial results, they might focus on one or two particular ideas and refine these even further. This could require another brainstorming session to generate ideas for new features that perhaps would enable the idea to interface with a bigger system. This "second time around" could be viewed as knowledge that was transferred out of the first design cycle, and put to immediate use in an effective way.

This back-and-forth approach as one generates and refines a design idea illustrates how process knowledge is utilized in a very iterative way. In this sense transferring in and out are not discrete events that happen at the beginning of a course (or learning event) and again at the end. In IDEA we expect students to use their knowledge in a more fluid way such that it is applied and reflected upon throughout the design/learning process.

We have conducted several studies to measure the type of design process knowledge that gets transferred into and out of our design experiences. We present here some results from a study we conducted in our first-year design course, Engineering Design and Communication (EDC), IDEA106. For this study we were interested in determining to what extent students bring design process knowledge into their first formal design experience in the IDEA curriculum. One of our goals for IDEA is to bring a learner-centered approach to our design education such that courses build on students' prior knowledge, and that the learning experiences in IDEA courses reinforces students' knowledge [11].

We presented students with a design scenario at the beginning of the course, and again at the end. "Design scenario" assignments have been used by various researchers to evaluate students' conceptions of design process and how these conceptions evolve over time [12, 13]. An example of one of our design scenarios is given below.

> "Assume that you are on a design team that has been hired by the Rehabilitation Institute of Chicago, the leading rehabilitation hospital in the country, to design a new device to help stroke patients open doors. Many individuals who have had a stroke are unable to perform bilateral tasks, meaning they have limited or no use of one upper extremity (arm/shoulder). It is particularly difficult for these people not only to unlock and turn the knob but also to push/pull the door open. Your design team has been asked to create a system that allows a person to unlock and open the door at the same time with one hand. Your design team accepts this challenge and goes to work. Map out a plan, describing how you intend to approach this project."

Student responses to the scenario assignment were coded according to a rubric, and their pre and post responses were compared. The coding was conducted such that if a student response mentioned an item given in the rubric the response received a '1' for this item, if not, the response received a '0'. A subset of the items from the rubric is given in Table 2.

Table 2: Sample items in rubric for coding design scenario responses.

A. Basic Design Process Strategies or Techniques
1. Generate alternatives
2. Prototype/mock-up, build model
3. Perform research (review competitive or similar products, conduct literature review on topic, investigate possible causes of problem(s) and existing solutions)
4. Define specifications, requirements, design constraints
5. Obtain feedback on an idea/design (users, peers, experts)
6. Brainstorm

Figure 2 provides the results for the pre and post data analysis. Student responses for all items shown in Figure 2 had significant gains at the $p < 0.01$ level. Based on our results we see that students transfer into their scenario response particular concepts about design process. For example, approximately 50% of the students in the pre-response talk about the importance of generating possible alternatives as part of the initial stages of design. Post results reveal that students build on all concepts that were identified in the pre responses.

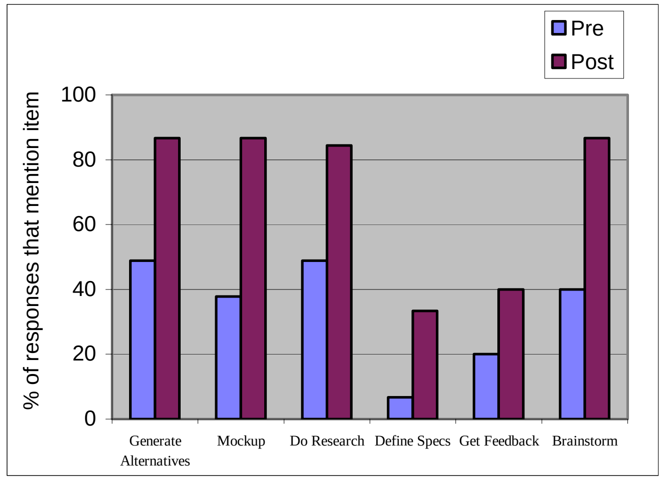

Figure 2: Pre and post responses to design scenario, N=45.

The results presented here are not being used to claim that students have developed adaptive expertise per se. Rather, the pre and post scenario assessment enables us to identify what design process knowledge gets transferred into the course and, furthermore, what gets transferred out. As educators, information about what transfers in and out of learning situations helps us understand the prior knowledge that students bring to courses. In particular, the results presented here help us understand students' conceptions of design process--which is critical to the project work in IDEA. As Scwartz et al. describe, this prior knowledge has major effects on subsequent thinking and cognitive processing and it serves as the "interpretations that shape how [one begins] to make sense of the situation."

The Innovation Dimension of IDEA

The dimension of innovation can be inclusive of many attributes associated with design and complex problem solving. For example, an innovative mind-set requires a level of determination and willingness to go beyond the routine (or just satisfactory solution). Other attributes associated with persistence include motivation and a desire to persist even when "times get tough." That is, unique or innovative solutions are ones that do not already exist. There is no template to follow, or closed form solution that theory dictates should be correct. As Schwartz et al. state, "innovation often requires a movement away from what is momentarily most efficient for the individual" [1, p. 30]. As educators we face the instructional challenge of how to create a learning environment that encourages students to not constrain the problem space, to persist when faced with difficulties, and to develop a willingness to open up their thinking to new possibilities, even at the expense of efficiency.

The education literature suggests a link between persistence and motivation, as well as several other affective attributes. For example, Hynd and coworkers explain that persistence and effort are outcomes of motivating influences such as "self efficacy, interest, a desire for good grades and a belief that the information is relevant and useful" [14, p. 55]. Hynd and coworkers suggest that, in order to support learning at the conceptual change level, instructors should present information by incorporating real life applications or uses so that students see the relevance of the information.

Furthermore, Keller has developed the "ARCS" model of motivation that provides a framework for understanding the major influences on the motivation to learn [15]. The ARCS model defines four major conditions that need to be met for people to become and remain motivated: attention, relevance, confidence, and satisfaction. In Keller's discussion of relevance he poses the question, "How many times have we heard students ask, 'Why do I have to study this?'" [15, p. 3]. IDEA students do not voice this question since the answer is intrinsic to the design activities within IDEA courses.

Since all of the IDEA design projects are actual design problems with real clients and users, the projects address the "relevance" condition of the ARCS model. Students consult with clients to define the project goals, meet with users to get feedback on different design ideas, and ultimately create solutions (often working prototypes) that are given to the client to be implemented and used. Through these authentic design activities students see first-hand the impact of their design solutions, and the relevance of their work in a broader context. Table 1 also includes a short description of the relevance of the projects.

We note that each of our IDEA projects exists because of a current need. Therefore, solutions do not already exist. It is the task of our IDEA design teams to be innovative with their knowledge to develop solutions to meet current needs. In this way, it is not enough for students to be "efficient". Efficiency alone will not satisfy the requirements for what is needed to address the challenge. IDEA projects, therefore, require students to also develop along the innovation dimension of adaptive expertise.

Courses and Pedagogy of IDEA

IDEA offers a certificate in engineering design program to all undergraduates. The certificate program focuses on innovative engineering design in a team-based, cross-disciplinary setting. In addition to EDC (IDEA106), two other design project courses serve as the required core to the certificate program. In these two courses, IDEA 298 and IDEA 398, students work in teams to solve problems as illustrated in Table 1. IDEA 106, required of all first year engineering students, serves as the foundation design course. IDEA 298 and 398 builds on the foundational EDC course and is taken by students in their junior or senior year.

We have adopted a two-part teaching approach for these project-based courses. One component of the course consists of addressing topics we have identified as critical to the design process such as ethics, project management, communication and teamwork. This component of the course is team taught by faculty from both the engineering school and the writing program. Many of the classes devoted to these topics use a case-based teaching approach and assignments are structured so that students discuss the topics in the context of their design project. By having students connect the learning with their actual project we emphasize relevance not only of the project, but also of the subject matter knowledge, or efficiency dimension, that enables productive completion of the project.

The other component of the course consists of carrying out the design project work. For this component of the course student teams are assigned a "project mentor", or coach. The project mentor is someone who can help guide the team through the design process and help teams bring the project to completion [16]. Our two-part teaching approach helps to integrate the dimensions of innovation and efficiency. That is, in our IDEA courses we want students to display skills they developed within their area of expertise (efficiency). The course assignments, case studies, and project-work contribute to the demonstration and development of efficiency.

However, the projects represent novel problems, or problems students have not yet encountered. Therefore, the projects in IDEA present situations where students are required to not only apply prior knowledge and skills, but also *generate new knowledge* and ideas that are useful for achieving a novel and appropriate goal. The project work embodies the innovation dimension of adaptive expertise in that students are expected to identify new directions and define and execute an appropriate plan of action to realize that new opportunity. The IDEA projects, and mentoring pedagogy are intended to facilitate students in developing the inquiry and self-regulating skills necessary to identify and comprehend a problem, identify what additional knowledge is necessary, as well as facilitate developing "design judgment."

DISCUSSION AND NEXT STEPS

In IDEA students work on design projects that require innovative solutions to real needs. In this paper we have discussed our curricular approach in the context of developing adaptive expertise. That is, we claim that a broader educational aim is to advance students along the path to adaptive expertise. To do so the educational experience should include a balance of innovation and efficiency, as presented in Fig. 1. We have included elements of both efficiency and innovation in our design curriculum to enable students to flexibly use disciplinary and design process knowledge to develop innovative solutions to current needs.

At the moment the literature on adaptive expertise is in the early stages and provides only a descriptive model for the dimensions that combine to move one along the path. The literature does not define precisely what these terms mean, nor does it prescribe how educators might conduct studies to measure adaptive expertise. In addition, the literature does not suggest how to create learning experiences to develop adaptive expertise, or characterize how one develops along the path. We view this as fertile ground to contribute to the literature on adaptive expertise, in particular how it applies to engineering education. We are particularly interested in the situational features that contribute to, or hinder the development of adaptive expertise. For example, we suspect that individuals choose to be adaptive in some situations, but opt not to in others. The judgment to be adaptive or not could be attributed to many factors that could fall along either the efficiency or innovation dimension, or both.

REFERENCES

1. 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., pp. 1-51.
2. 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, pp. 262–272.
3. Hatano, G., and Oura, Y., 2003, "Commentary: Reconceptualizing School Learning Using Insight From Expertise Research," *Educational Researcher*, 32(8), pp. 26–29.
4. Pandy, M.G., Petrosino, A.J., Austin, B. and Barr, R., 2004, "Assessing Adaptive Expertise in Undergraduate Biomechanics," *Journal of Engineering Education* 93, pp. 211-222.
5. Crawford, V. M., Schlager, M., Toyama, Y., Riel, M., & Vahey, P., 2005, "Characterizing adaptive expertise in science teaching: Report on a laboratory study of teacher reasoning," Paper presented at the Annual Conference of the American Educational Research Association, April 11–15, 2005, Montreal, Canada.
6. McKenna, A. F., Colgate, J. E., Carr, S., and Olson, G. B.,2006, "IDEA: Formalizing the Foundation for an Engineering Design Education," *International Journal of Engineering Education*, 22(1), in press.
7. Hirsch, P., Shwom, B., Yarnoff, C., Anderson, J., Kelso, D., Olson, G., and Colgate, J.E., 2001, "Engineering Design and Communication: the Case for Interdisciplinary Collaboration," *International Journal of Engineering Education*, 17(4).
8. Cosgrove, J., Heng Y. C., Lahey, M., and Lizak, P., 2005, "Infant Feeder for HIV+ Mothers," Report submitted to fulfill requirements for IDEA 298/398: Interdisciplinary Design Projects, Northwestern University.
9. Gutierrez, C., Rodriguez, D., and Ojalvo, J., 2005, "NUberwalker Business Plan", Report submitted to fulfill requirements for IE 325: Engineering Entrepreneurship, Northwestern University.
10. Schon, D.A.., 1987, "Educating the Reflective Practitioner," San Francisco, CA: Josey Bass Inc.
11. 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.
12. McMartin, F., McKenna, A., and Youseffi, K., 2000, "Scenario Assignments as Assessment Tools for Undergraduate Engineering Education," *IEEE Transactions on Education*, 43(2), pp. 111-119.
13. Atman, C. J. and Turns, J., 2001, "Studying Engineering Design Learning: Four Verbal Protocol Studies," In C. Eastman, W. McCracken, & W. Newstetter (Eds.), *Design Knowing and Learning: Cognition in Design Education*, Oxford, England: Elsevier Science Ltd.
14. Hynd, C., Holschuh, J., and Nist, S., 2000, "Learning Complex Scientific Information: Motivation Theory And its Relation to Student Perceptions", *Reading &Writing Quarterly*, 16(1), pp. 23–57.
15. Keller, J.M., 1987, "Development and Use of the ARCS Model of Instructional Design," *Journal of Instructional Development*, 10(3).
16. McKenna, Ann, F., Colgate, J. Edward, Olson, Gregory, B. (2006). Characterizing the Mentoring Process for Developing Effective Design Engineers, *Proceedings of the American Society for Engineering Education (ASEE) Annual Conference,* ASEE 2006, Chicago, IL.

