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The Informed Design Teaching and Learning Matrix

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Background
Design experiences play a crucial role in undergraduate engineering education and are increasingly important in K–12 settings. There are few efforts to purposefully connect research findings on how people design with what teachers need to understand and do to help K–16 students improve their design capability and learn through design activities.

Purpose
This paper connects and simplifies disparate findings from research on design cognition and presents a robust framework for a scholarship of design teaching and learning that includes misconceptions, learning trajectories, instructional goals, and teaching strategies that instructors need to know to teach engineering design effectively.

Method
A scholarship of integration study was conducted that involved a meta-literature review and led to selecting and bounding students' design performances with appropriate starting points and end points, establishing key performance dimensions of design practices, and fashioning use-inspired tools that represent design pedagogical content knowledge for teachers.

Results
The outcome of this scholarship of integration effort is the Informed Design Learning and Teaching Matrix that contains nine engineering design strategies and associated patterns that contrast beginning versus informed design behaviors, with links to learning goals and instructional approaches that aim to support students in developing their engineering design abilities.

Conclusions
This paper's theoretical contribution is an emergent educational theory of informed design that identifies key performance dimensions relevant to K–16 engineering and STEM educational contexts. Practical contributions include the Informed Design Teaching and Learning Matrix, which is fashioned to help teachers do informed teaching with design tasks while developing their own design pedagogical content knowledge.

Keywords
engineering design, scholarship of integration, pedagogical content knowledge

Introduction

Design has been a prominent topic in shaping undergraduate engineering education and the engineering profession. Reports on the goals of engineering education in the United States and internationally (e.g., Mann, 1918; SPEE, 1930; Harris et al., 1994; Goals Committee, 1968; Spinks et al., 2006) consistently identify design as central to engineering education. Bucciarelli (2003) considers design knowledge and knowing essential elements of an epistemology of engineering. Figueiredo (2008) describes four key dimensions related to the nature of engineering: the basic sciences (engineer as scientist), the human sciences (engineer as humanist), design (engineer as designer), and the crafts (engineer as craftsworker). While proposed definitions of design are legion, for the purpose of this paper, we see design as a goal-directed problem-solving activity (Archer, 1965) that initiates change in human-made things (Jones, 1992), and involves optimizing parameters (Matchett, 1968) and balancing trade-offs (AAAS, 2001) to meet targeted user needs (Gregory, 1966).

Design experiences are also playing a more substantive role in precollege students' STEM (science, technology, engineering, and mathematics) education and career preparation. While some form of design capability has appeared in various national K–12 standards as a separate and distinct learning objective (AAAS, 1993; NRC, 1996; ITEA, 2000), until recently design challenges have been employed in K–12 settings more often as performance projects (Kanter, 2010, p. 526) for learning concepts other than engineering. They have been used as contexts to teach mathematics (Jacobson & Lehrer, 2000), science (Sadler, Coyle, & Schwartz, 2000; Kolodner et al., 2003; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004), computer programming (Kafai, Ching, & Marshall, 1997), music (Bamberger, 2003), design and technology in the United Kingdom (Kimbell, Stables, Wheeler, Wozniak, & Kelly, 1991; Barlex, 1995, 2000), and technology education topics in the United States (LaPorte & Sanders, 1995; Hacker & Burghardt, 2004). Design-based learning experiences have been found to improve student learning and achievement in mathematics and science – although these results are not always consistent (Kanter, 2010, p. 3; Petrosino, 1998) – and to enhance students' interest in STEM subjects (Committee on Engineering Education in K–12, 2009).

These trends continue to evolve – in some cases merging and in other cases remaining distinct and separate. A recent National Assessment of Educational Programs (NAEP) initiative has formulated a plan to assess U.S. eighth-grade students in technological literacy and engineering design in 2014. The Committee on K–12 Engineering Education (2009) recommended that learning engineering design become a key feature of K–12 engineering education after finding that significant learning in preschool through high school classrooms was associated with the use of extended design activities that were presented in meaningful contexts. The Committee on Standards for K–12 Engineering Education, however, did not recommend developing separate content standards for engineering education in K–12 settings (NAS, 2010). Instead, it urged the infusion and mapping of engineering learning goals, topics, and skills into the standards of other STEM disciplines. This approach has been adopted by the National Academy of Science in its *Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (2012), where "engineering and technology are featured alongside the natural sciences." One consequence of K–12 schools adopting this approach will be that many students' first encounters with design activities will happen under the watchful eyes of teachers with few to no design experiences under their belts and little training in using these activities.

Advancements in the scholarship of design teaching and learning must therefore address two significant needs. First, the field lacks a coherent representation of design pedagogical content knowledge (Design PCK), despite the fact that it has produced a rich body of research findings and hundreds of prescriptive and descriptive design process models (Dubberly, 2004; Andrews & Goodson, 1980), as well as consensus models for engineering and architectural/industrial design (Roozenburg & Cross, 1991). Design PCK is content-specific, specialized teacher knowledge associated with instructional techniques that are particularly suited to teaching effectively with design tasks (see Shulman, 1986). It entails knowing typical trajectories that different students can follow when learning engineering design, the misconceptions and inefficient habits of mind to which beginning designers are prone, and relevant learning goals that can help students acquire competency in design in a timely fashion. Design PCK is distinguished from *design content knowledge*, which includes facts, concepts, and models related to design, and *general pedagogical knowledge* that teachers need to know to do effective classroom and time management, lead whole-class or small-group discussions, and help establish a classroom culture for a community of learners.

While many have been motivated to integrate design into K–12 curricula or further its use in undergraduate engineering education, these efforts have proven to be difficult, nontrivial endeavors. In precollege settings, teachers using design projects can miss critical opportunities to support the meaningful learning of STEM concepts in students (Kanter, 2010). Lacking the knowledge needed to teach effectively with design challenges (Hynes, 2010), they may inadvertently model for students inefficient design behaviors and habits of mind or reinforce students' design misconceptions. Such teachers may be less reflective about the actionable knowledge that they generate while teaching (Schön, 1995), or may become uncritical users when implementing textbook-based design process models that do not fully represent the space of design learning (see Adams, Turns, & Atman, 2003; Mosborg et al., 2005) or the kinds of judgment necessary to choose one strategy over another (Bransford, Franks, Vry, & Sherwood, 1989). For example, following a design process model step-by-step may inadvertently communicate to learners that design is a set of linear steps to be followed regardless of the situation, which can make students less adept at switching design strategies when needed, transitioning among subproblems within the larger design challenge (Strobel & Pan, 2011), or potentially less ready to deal with the ambiguities of ill-defined problems (e.g., Adams et al., 2003; Cross, 2001; Daly, Adams & Bodner, 2012; Lande & Leifer, 2010).

A second need for an integrative scholarship in engineering design is to help K–16 teachers access and interpret implications from design cognition research and render it usable for everyday classroom teaching. This also is not a trivial endeavor: design cognition and learning research spans extremely diverse disciplines, such as engineering, software design, architecture, writing, product design, and cross-disciplinary areas like sustainable design, biomedical design, nanotechnology, and human-centered design. Research suggests that undergraduate teachers, who may have considerable disciplinary and experiential knowledge, rarely read design research or disseminate their effective design teaching approaches to others (Pembridge & Paretti, 2010), although there are exceptions (Terpenny & Goff, 2005). When they do publish, they do not reference the broader body of research (Martin, Adams, & Turns, 2002). In other words, the problems of linking educational research with teaching practice, which have been noted in other fields of STEM education (Turns et al., 2006; Arbaugh et al., 2010), hold as well for engineering design education. Strengthening ties between research and practice may support the use of evidence-based decision making when choosing and sequencing instructional strategies and assessments, and may also lay the groundwork for the development of empirically verifiable models of learning progressions.

Learning progressions are conjectural models that take a stance regarding the nature and sequencing of skills and ideas that learners should develop over time. They may be empirically tested through validation studies, cross-sectional studies, and sequential studies (Duncan & Hmelo-Silver, 2009) to determine the degree to which the underlying cognitive models hold true in different settings and for different learners. These progressions may serve as templates for designing curricula and assessments (Songer, Kelcey, & Gotwals, 2009) and help teachers select appropriate learning goals and instructional activities (NRC, 2007), better understand what student behaviors or strategies to be watchful for when teaching, enhance their reflective practice, and build in-depth Design PCK. Learning progressions may also serve as templates for professional development products (Songer et al., 2009) and guide the evaluation of programs that promise to foster more sophisticated thinking about a topic or skill by means of multiple learning experiences over time (Songer et al., 2007; NRC, 2007).

The "scholarship of integration" (Boyer, 1990) can meet these needs by synthesizing a broad and unwieldy research base to create a use-inspired framework and tools that can enable teachers to construct their own Design PCK. The scholarship of integration is "serious, disciplined work that seeks to interpret, draw together and bring new insight to bear on original research . . . fitting one's own research – or the research of others – into larger intellectual patterns" (Boyer, 1990, p. 19). This requires an integrative and potentially transdisciplinary synthesis that can bring together ideas across multiple perspectives. Kezar (2002) makes a compelling argument that the goal of such work benefits researchers, educators, and policymakers by pulling together various studies in a comprehensive way that gives "meaning to isolated facts and putting them into perspective" and overcomes a tendency to "split knowledge into ever more esoteric bits and pieces." In the case of engineering design education, the scholarship of integration may help support dialectic and interactive cycles that link practical questions about design teaching with research questions about design learning trajectories (Booth, Colomb, & Williams, 2008). The fruits of such a process could help educators set more precise learning goals and select from a wider array of instructional strategies and assessments when creating and implementing design-based activities.

In the following sections we first discuss our scholarship of integration approach and then present the outcomes of this process: the formulation of the idea of informed design, the depiction of Design PCK as the Informed Design Learning and Teaching Matrix, and a review of the research base to support these ideas. We conclude the paper with a discussion of the Matrix as an emergent instructional theory from which research questions can be generated and findings can be integrated, including results from testing the efficacy of different instructional methods, and provide practical examples of how teachers may use the Matrix to improve their classroom instruction and build their own Design PCK.

CONDUCTING A SCHOLARSHIP OF INTEGRATION STUDY

This section describes the scholarship of integration approach that was used to articulate the central notion in this paper of informed design and to create the Informed Design Teaching and Learning Matrix (Table 1) associated with it. The Matrix presents nine critical design practices or strategies and provides contrasting pattern statements that juxtapose how beginning versus informed designers do them. The table links these items to lists of learning goals and instructional strategies that teachers may use to support learners in becoming informed designers.

The scholarship of integration has been slower than other forms of scholarship to gain acceptance as an integral activity in academia. Some reasons for this include the isolation of the disciplines, the view that interdisciplinary work is risky and located on the margins of academic endeavors, the difficulty of the task, and a perceived disconnect between the scientific community, the world of practitioners, and the larger public (Dauphinée & Martin, 2000; Hofmeyer, Newton, & Scott, 2007; Kezar, 2002). Hofmeyer et al. (2007) note, however, that this form of scholarship is becoming more central to academic work because it is better equipped to build interdisciplinary partnerships, develop frameworks that transcend disciplinary paradigms, and respond to complex, multifocal, contemporary issues at the individual and societal level. While there are few examples of the scholarship of integration, a review reveals certain shared attributes or goals. In the biomedical sciences, one scholarship of integration effort focused on making connections across science disciplines, educating specialists, and placing the work of individual investigators into a larger context (Dauphinée & Martin, 2000). In business management, this form of scholarship has helped identify implications for practice that were not effectively communicated in scholarly publications (Bartunek, 2007). In the health sciences, it has sought to address how translational medicine, which adapts and converts findings from animal studies to human studies, gets lost in translation, how an overabundance of information can be processed into a useful compendium, and how feedback from clinics can help create and test novel therapies (Mankoff, Brander, Ferrone, & Marincola, 2004). These examples illustrate themes of cycling between research and practice (Booth et al., 2008; Kezar, 2002) and of moving beyond syntheses towards the creation of use-inspired frameworks. Turns et al. (2006) identify the following goals for synthesizing research for practical use in the context of engineering design education: support evidence-based decision making, answer practical questions of high concern, promote reflective practice, and improve pedagogical content knowledge in teachers.

A three-phase process for conducting a scholarship of integration study was used in this paper. This process was based on examples of work in other disciplines (Dauphinée & Martin, 2000; Kezar, 2009) as well as the concepts of use-inspired design (Turns et al., 2006), learning progressions (NRC, 2007; Duncan & Hmelo-Silver, 2009), and pedagogical content knowledge (Shulman, 1986). The first phase involves bounding design performances within generic starting points and end points that are appropriate learning targets for student designers. These in turn would guide what research to review and how it should be interpreted and compiled. The second phase involves conducting a meta-analysis that acts as a form of discovery in itself (Hofmeyer et al., 2007), where the intended outcome is a set of key performance dimensions pertinent to the selected learning targets (Duncan & Hmelo-Silver, 2009). The third phase involves representing these performance dimensions as a parsimonious set of observable patterns that denote progressions in design learning, and incorporating these patterns into a use-inspired tool for teachers and researchers. This tool aims to enable teachers to develop their own Design PCK – including their ability to observe and recognize the highly ineffective practices and habits of mind that beginning designers employ, select learning goals, choose appropriate teaching strategies when using design tasks, and assess students' growth in design practices. An additional goal is to facilitate empirical validation studies that will help in developing an instructional theory of engineering design for K–16 students. The following paragraphs provide details of this scholarship of integration approach.

Bounding Typical Student Designer Performances

Bounding student design performance requires identifying appropriate starting points and realistic end goals for K–16 design learners. Duncan and Hmelo-Silver (2009) suggest that when creating a learning progression it is useful to identify (1) a lower anchor that describes assumptions about the prior knowledge and skills of learners as they enter a progression and (2) an upper anchor that depicts what learners are expected to know and do by the end of a progression. While cognitive and learning scientists have long favored contrasting the work and thinking of experts with novices, the range of definitions that these researchers have employed for what constitutes a novice, however, has varied greatly. Even graduate students have been classified as novices; for example, see Chi, Feltovich, and Glaser's (1981) often-cited novice-expert study of surface- versus deep-feature recognition of problem sets in physics. The framework developed in this paper builds upon a three-stage model of developing design expertise that includes naive, novice, and expert levels of performance (Crismond 1997, 2001). Researchers have described telling differences between naive and novice levels of practice in various endeavors including performing science tasks (Zajchowski & Martin, 1993), solving physics problems (Chi & Bassok, 1988), learning nursing (Benner, Tanner, & Chesla, 1996), and doing wine tasting (Solomon, 1997).

The starting point selected for this framework to depict a baseline in design capability is the behavior and thinking of students with little or no experience and no formal training in designing – the beginning designer. The end point in design capability is that of the "informed designer," whose level of competence lies somewhere between that of the novice and expert designer, and in other learning contexts might be called an "advanced novice" (Dreyfus, 2005), "expertlike novice" (Bereiter & Scardamalia, 1993), "expert student" (Sternberg, 1997), or "competent performer" (Dreyfus & Dreyfus, 1986). Informed designers will have had some formal training in design, and although not necessarily older than beginning designers, will possess some design experience. The idea of a designer who is informed grew out of a book of essays by David Hawkins called *The Informed Vision* (2002), and alludes to notions of the engaged and knowledgeable citizen, to the wary and savvy consumer, and has previously been applied to the context of learning and doing engineering design (Crismond, Kolodner, Fasse, Gray, & Holbrook, 1999; Burghardt & Hacker, 2004; Crismond, 2005).

This midrange stage of the informed designer maps well onto a generic model of design expertise that corresponds to ways of perceiving, interpreting, structuring, and solving complex problems (Dreyfus, 2005; Lawson & Dorst, 2009). As such, it is a more appropriate end point for school-based designers than design expertise. In many fields, expertise, which involves deliberate practice and the use of well-connected and hierarchically organized knowledge structures to solve problems (Dufresne, Gerace, Hardiman, & Mestre, 1992) takes 10 or more years to achieve (Hayes, 1989). Students in K–16 learning settings are not likely to accumulate the level of authentic practice necessary to develop expert-like behaviors, although there are some exceptions (Atman, Chimka, Bursic, & Nachtmann, 1999). While experts notice salient patterns quickly and have available much situation-specific knowledge and many easily remembered cases available for recall (Bransford, Brown, & Cocking, 1999), informed designers may hold fewer experiential cases in mind and lack extensive practice in a domain. Compared to experts, informed designers' pattern-matching skills would be less reliable, and their retrieval and use of learned ideas would be done less flexibly, since those ideas would have fewer connections to other thoughts. Their understandings would also be more situation-dependent and wedded to their originally learned contexts. Piaget made note of a similar tendency in cognitive systems that were still in formation (De Lisi & Goldbeck, 1999, p. 7).

Generating Performance Dimensions

Generating performance dimensions of informed designing involves a multidisciplinary scholarship of integration process to bring together diverse knowledge sources and identify in a comprehensive way an inclusive set of intellectual patterns (Boyer, 1990). It is a process of discovery (Hofmeyer et al., 2007) that aims to overcome knowledge isolation and fragmentation (Kezar, 2002), while managing the trade-offs between simplicity and parsimony when describing the complexities of learning (Lehrer & Schauble, 2009).

Identifying, reviewing, and uniting the broad literatures of design cognition research is a nontrivial task. The literature spans many disciplines, making it difficult to navigate, synthesize, and translate specific findings into recommendations for design teaching. There are more than 170 peer-reviewed design journals, of which over 30 identify engineering design as a primary subject of interest to their audiences (e.g., *Design Studies, Design Issues, Research in Engineering Design*, *Journal of Mechanical Design*, *Journal of Design and Technology Education*, *Design Theory and Methodology,* and *Leonardo*). Many other journals treat engineering design as a topic of interest (e.g., *Journal of Engineering Education*, *International Journal of Engineering Education*, *Journal of the Learning Sciences*, *Cognition & Instruction, Cognitive Science, Journal of Research in Science Teaching,* and *Performance Improvement Quarterly*). Three additional challenges of this effort are that syntheses of design cognition, learning, and teaching are not common, that terminologies from different design domains can carry different meanings, and that studies report on a wide range of ages and grade bands. While there are many useful design textbooks and anthologies, they often emphasize design techniques (e.g., Dym & Little, 2004; Cross, 2000; Pahl & Bietz, 1995) over how people learn design, and the anthologies often target design researchers rather than design educators as their primary audience (e.g., Eastman, Newstetter, & McCracken, 2001; Visser, 2006).

There are, however, exceptions to these trends. Kimbell, Stables, and Green (1996) propose progressions in design capability for a series of specific "facets of performance" (p. 49) that include investigating, planning, modeling and making, design issues, evaluating, extending knowledge and skill, and communicating. The authors also describe student performances and teaching approaches for each design facet at four different grade bands. Similarly, Lawson and Dorst (2009) published a book to help design practitioners learn about and reflect upon their own development, design educators think about their teaching and students learning, and design researchers connect to a broad body of research.

The following key performance dimensions, which are limited to foundational and generative ideas and practices (Duncan & Hmelo-Silver, 2009), were identified as central to doing informed design.

Learning while designing Informed designers are involved in continual learning (Lawson & Dorst, 2009): learning by doing, learning from brainstorming and prototyping, learning by iteration and from feedback and failure, learning by noticing and troubleshooting, learning by drawing and dialoging with ideas, materials, and people, and learning from reflection. All of these emphasize the metacognitive and reflective practice aspects of learning through design (Schön, 1987). One cognitive model of design emphasizes that "learning is central and inherent to designing" (Adams & Atman, 2000), in which designers continuously co-construct understandings of problems and possible solutions. In contrast, the learning that beginning designers achieve is often not articulated and is so fleeting and ephemeral that "conceptual closure is not attained" (Burghardt & Hacker, 2004).

Making and explaining knowledge-driven decisions Informed designers use their understanding of physical laws (Mann, 1981), of how things work, of methods of construction (Zubrowski, 2002a, p. 57), and insights from experiments they conduct to help make and explain their design decisions. This involves yet goes beyond "common sense and everyday knowledge" (McCormick, 1993), a designer's "craft-based" application of known cases (Cross, 1999), and "intuition resolution" (Alexander, 1964, p. 5), and includes knowledge gained from revisions made as a design evolves (Perkins, Crismond, Simmons, & Unger, 1995, pp. 72–73).

Working creatively to generate design insights and solutions Creativity and innovation are cornerstones for all design work (Visser, 1996; Milne & Leifer, 1999; Shah & Vargas-Hernandez, 2002; Barlex, 2011) both in the workplace and in schools. Design must be informed by the creative insights (Smith, 1997, p. 143) that get generated when framing a problem, generating potential solutions, and proposing novel ways to troubleshoot and iteratively improve prototypes. Helping students learn to deal with uncertainty and to take productive risks while working with their ideas in creative ways can enhance such work.

Perceiving and taking perspectives intelligently Informed designers achieve a perspective on the overarching goals and big picture in a product's development that helps them establish intentions and priorities in their design work (Christiaans & Dorst, 1992, p. 135). They use empathy when imagining the experiences of products from the viewpoints of a wide variety of users (Brown, 2009, p. 49). They can also employ "perceptive observation" where they "learn what to focus on and what is relevant" (Kolodner & Wills, 1996) in order to detect positive and negative behaviors in a product's performance.

Conducting sustained technological investigations Informed designers collect, organize, and analyze evidence and develop critical standards for performing technological investigations and evaluating critical questions related to the device or system they are developing. Such work is analogous to scientists doing sustained inquiry when investigating phenomena in nature (Erickson & Lehrer, 1998).

Using design strategies effectively Informed designers possess a range of design practices and strategies, know when and how to use them (Adams, Turns, & Atman, 2003), and can alter their approaches to accommodate constraints of time and budget (Wedman & Tessmer, 1991). They also work effectively in groups and can decide what information sources to draw upon and what past experiences to apply most effectively when addressing any number of problems embedded in a design challenge.

Integrating and reflecting on knowledge and skills Informed designers employ an "integrated capability" where action, appraisal, and reflection are used in concert rather than in isolation (Kimbell et al., 1991, p. 156) as they transition among the "intertwined . . . compound problems" associated with design (Strobel & Pan, 2011). They combine skills in design and fabrication with formal and everyday understandings of relevant disciplines to create technological solutions (McCormick, 1994).

As can be seen from the reference section of this paper, the following journals and conference proceedings were most represented in this synthesis: *Design Studies* (27 articles cited), *Proceedings of the Annual Meeting of the American Society of Engineering Education Conference* (12), *Journal of Research in Science Teaching* (9), *International Journal of*

Engineering Education (9), *International Conference on Design and Technology Educational Research and Curriculum Development [IDATER]* (9), *Research in Engineering Design* (8), *Journal of Engineering Education* (7), and *Journal of the Learning Sciences* (4). The other sources were represented to a far lesser extent. Studies in these publications reported on a wide range of subjects, from young learners to practicing adult professionals, and performances at different levels of design expertise, from rank tyro to expert designer.

Translating Performance Dimensions

The process of translating performance dimensions of informed designing into a use-inspired, research-based instructional tool was accomplished through the following steps. The first step involved selecting a parsimonious set of nine observable design strategies that are fundamental to the performance dimensions of informed design identified in the previous section. Four criteria were used in making these selections: (1) criticality, strategies should be relevant and critical to design thinking and learning; (2) observability, strategies should be observable or teachable by classroom instructors; (3) frequency, strategies should be used multiple times during a design effort; and, (4) communicability, descriptions of strategies should make sense to non-designers.

The second step involved formulating "contrasting set" statements (Bransford et al., 1989) that would be memorable to teachers and act as a guide for noticing how *beginning* versus *informed* designers do the selected strategies. Each of the nine statements begins by describing the telltale signs of beginning designers' less effective approaches to implementing that strategy, and ends with a contrasting depiction of how informed designers would more effectively perform that same strategy (see Table 1). Taken together, they work as a collection of two-step learning progression statements related to many (but not all) elements that make up an effective practice of engineering design.

The final step was to place these statements into a single-table format that could be easy for teachers to use and help develop their "professional vision" (Goodwin, 1994) as informed users of design activities with students. The Matrix (Table 1) starts off by identifying a collection of nine design strategies (column 1), ones that could be found in any of a number of models of the design process. It then identifies some of the highly ineffective habits that beginning designers are prone to use (column 2), which are paired with descriptions of the same strategies as done by informed designers (column 3). The Matrix then attempts to articulate learning goals that are linked to the behaviors of informed designers (column 4), and then identifies examples of teaching approaches aimed at helping students reach those objectives (column 5).

Taken as a whole, the Matrix acts as an integrated framework that aims to facilitate growth of Design PCK in teachers, improve design capability and practice in learners, and help researchers advance the scholarships of design cognition, learning, and teaching for engineering education. While the strategies and patterns listed in the Matrix (columns 1–3) may also be seen as orthogonal to what might constitute contextualized knowledge about design, the ordering of strategies should not be viewed as an implicit suggestion that they be performed lock-step in a given or preferred sequence.

Figure 1 summarizes how the nine contrasting patterns found in the Matrix map to key performance dimensions associated with doing informed design. As shown here, the same performance dimension may be associated with more than one Matrix pattern. Certain performance dimensions, such as "learning while designing" and "connecting and reflecting on knowledge and skills," are associated with all Matrix patterns.

Unpacking the Matrix

In this section, we unpack and elaborate upon each of the nine contrasting patterns found in the Informed Design Teaching and Learning Matrix by providing more detailed descriptions of beginning and informed designers' strategies, and situating them in the research literature to illustrate their empirical base. The teaching strategies that are briefly mentioned in the right-most column of the Matrix are also described in greater detail, with citations provided when available. It should be noted that while some of these instructional approaches have undergone empirical testing, others have not, which highlights a critical need for future educational research. While we have tried to represent ideas at a broad level, disciplinary differences in teaching design suggest that not all teaching strategies will be appropriate for all settings and grade levels. On the other hand, some teaching strategies may be useful in addressing more than one learning goal and Matrix pattern.

Matrix Pattern A. Problem Solving vs. Problem Framing

The Strategy of Understanding the Design Challenge Beginning designers *feel that understanding the design challenge is straightforward, and a matter of comprehending the basic task and its requirements. By perceiving the design task as a well-structured problem and believing there is a single correct answer, they can act prematurely and attempt to solve it immediately.* Informed designers *seek initially to understand the challenge as best they can, but then delay making design decisions in order to explore and comprehend the design challenge more fully. They set out to learn through research, brainstorming, and doing technological investigations what the critical issues are in order to frame the problem effectively. They will later return to assess this framing after attempting to solve the challenge.*

Observing the initial moments after beginning designers are given a design problem, especially younger children, will probably reveal some team members quickly grabbing some materials and attempting to solve the problem with little talk and forethought, or immediately devising plans to solve the problem (Christiaans & Dorst, 1992, p. 132). They are making "premature commitments" (Cross, 2000) to initial solutions. Beginning designers must "frame a problematic design situation" (Schön, 1988), even though it may be done impulsively, superficially, or without an awareness of the implicit assumptions built into that framing. They may generate solutions prematurely because they assume that all that they needed to know has been provided for them in the problem statement or design brief, and do not believe that additional information is needed before they should start generating solutions (Rowland, 1992). They can treat design challenges much as they would well-defined, end-of-chapter textbook problems (Rowland, 1992, p. 74; Atman & Bursic, 1996, p. 249) with clearly articulated initial states, identifiable collections of known variables, and set procedures for generating solutions that can be evaluated unambiguously (Jonassen, 1997, p. 68). Studies involving other problem-solving domains report that novices tend to oversimplify the problems they face and begin their work by suggesting solutions almost immediately (Elio & Scharf, 1990).

Beginning designers do not fully grasp just how complicated, fluid, and changeable design problem-solving landscapes can be (Dorst, 2004), and can be unaware or unwary of their potential for cascading complexity. For others with more experience, design tasks are seen as "ill-structured" (Simon, 1984, pp. 152–153), and even "wicked" (Churchman, 1967; Rittel & Webber, 1984; Buchanan, 1995) because they are often ill-defined and

TABLE 1. The Informed Design Teaching and Learning Matrix.
This table links nine design strategies (Column 1) to contrasting pattern titles (across Columns 2 and 3) and statements of how beginning designers (Column 2) versus informed designers (Column 3) do those strategies, and to relevant learning goals (Column 4) and instructional approaches (Column 5) that teachers can use.

DESIGN STRATEGIES	BEGINNING vs. INFORMED DESIGNER PATTERNS		LEARNING GOALS WHERE STUDENTS…	TEACHING STRATEGIES WHERE STUDENTS…
	WHAT BEGINNING DESIGNERS DO	WHAT INFORMED DESIGNERS DO		
	Pattern A. Problem Solving vs. Problem Framing			
Understand the Challenge	Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve.	Delay making design decisions in order to explore, comprehend and frame the problem better.	Define criteria and constraints of challenge. Delay decisions until critical elements of challenge are grasped.	State criteria and constraints from design brief in one's own words Describe how preferred design solution should function and behave Reframe understanding of problem based on investigating solutions
	Pattern B. Skipping vs. Doing Research			
Build Knowledge	Skip doing research and instead pose or build solutions immediately.	Do investigations and research to learn about the problem, how the system works, relevant cases, and prior solutions.	Enhance background knowledge, and build understandings of users, mechanisms and systems.	Do info searches/read case studies Write product history report Do studies/research on users Reverse engineer existing products Conduct product dissections
	Pattern C. Idea Scarcity vs. Idea Fluency			
Generate Ideas	Work with few or just one idea, which they can get fixated or stuck on, and may not want to change or discard.	Practice idea fluency in order to work with lots of ideas by doing divergent thinking, brainstorming, etc.	Generate range of design ideas to avoid fixation. Know guidelines/reasons for various divergent thinking approaches.	Do brainstorming and related techniques to achieve idea fluency Relax real-world constraints or alter original task to see it in new ways Do generative database searches
	Pattern D. Surface vs. Deep Drawing & Modeling			
Represent Ideas	Propose superficial ideas that do not support deep inquiry of a system, and that would not work if built.	Use multiple representations to explore and investigate design ideas and support deeper inquiry into how system works.	Explore and investigate different design ideas via sketching, modeling solutions, and making simple prototypes.	"Mess about" with given models Use words, gestures, artifacts to scaffold visualizing solutions Do rapid prototyping using simple materials or various drawing tools Conduct structured review of ideas

Continues

TABLE 1. *Continued*

Weigh Options & Make Decisions	**Pattern E. Ignore vs. Balance Benefits & Tradeoffs**		Consider both the benefits and tradeoffs of all ideas before making design decisions.	Give explanations for design choices Describe/portray pros and cons for all design options under consideration Articulate design values and advice like KISS (Keep It Super Simple) and human-centered design
	Make design decisions without weighing all options, or attend only to pros of favored ideas, and cons of lesser approaches.	Use words and graphics to display and weigh both benefits and tradeoffs of all ideas before picking a design.		
Conduct Experiments	**Pattern F. Confounded vs. Valid Tests & Experiments**		Run valid "fair test" experiments to learn how prototypes behave and to optimize their performance.	Create design advice for others and generalizations based on valid tests Do investigate-and-redesign and product comparisons tasks Do tests to optimize performance
	Do few or no tests on prototypes, or run confounded tests by changing multiple variables in a single experiment.	Conduct valid experiments to learn about materials, key design variables and the system work.		
Troubleshoot	**Pattern G. Unfocused vs. Diagnostic Troubleshooting**		Diagnose and troubleshoot ideas or prototypes based on simulations or tests.	Follow troubleshooting steps: observe, name, explain, and remedy Do troubleshooting stations/videos Do modeling or cognitive training in troubleshooting
	Use an unfocused, non-analytical way to view prototypes during testing and troubleshooting of ideas.	Focus attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them.		
Revise/Iterate	**Pattern H. Haphazard or Linear vs. Managed & Iterative Designing**		Manage project resources and time well. Use iteration to improve ideas based on feedback. Employ design strategies repeatedly in any order as needed.	Student use design storyboards to record progression of their work Give instruction and scaffolding for project management & design steps Encourage taking risks, learning while iterating, and reflecting on how the design problem is framed
	Design in haphazard ways where little learning gets done, or do design steps once in linear order.	Do design in a managed way, where ideas are improved iteratively via feedback, and strategies are used multiple times as needed, in any order.		
Reflect on Process	**Pattern I. Tacit vs. Reflective Design Thinking**		Periodically reflect while designing and keep tabs on strategies used. Review to check how well solutions met goals.	Keep design diaries and portfolios Compare/contrast design cases of approaches used by different groups Do computer-supported structured reflections about design work
	Do tacit designing with little self-monitoring while working or reflecting on the process and product when done.	Practice reflective thinking by keeping tabs on design strategies and thinking while working and after finished.		

MATRIX PATTERNS: BEGINNING VS. INFORMED DESIGNERS / DIMENSIONS OF INFORMED DESIGN	LEARNING WHILE DESIGNING	MAKING KNOWLEDGE-DRIVEN DECISIONS	WORKING CREATIVELY TO GENERATE DESIGN INSIGHTS & SOLUTIONS	PERCEIVING & TAKING PERSPECTIVES INTELLIGENTLY	CONDUCTING SUSTAINED TECHNOLOGICAL INVESTIGATIONS	USING DESIGN STRATEGIES EFFECTIVELY	CONNECTING AND REFLECTING ON KNOWLEDGE AND SKILLS
A. Problem Solving vs. Problem Framing	•	•	•	•		•	•
B. Skipping vs. Doing Research	•	•		•	•	•	•
C. Idea Scarcity vs. Idea Fluency	•		•			•	•
D. Surface vs. Deep Drawing & Modeling	•	•	•		•	•	•
E. Ignore vs. Balance Benefits & Trade-offs	•	•		•		•	•
F. Confounded vs. Valid Tests & Experiments	•	•			•	•	•
G. Unfocused vs. Diagnostic Troubleshooting	•	•		•	•	•	•
H. Haphazard or Linear vs. Managed & Iterative Designing	•	•	•	•	•	•	•
I. Tacit vs. Reflective Design Thinking	•	•				•	•

FIGURE 1. Mapping the contrasting patterns of the Matrix to key dimensions of informed design.

involve elements and parameters that are only partially determined at the outset of work. Design tasks can require understandings from an "extensive and unpredictable" range of disciplines (McCormick, 1993, p. 309), and can swamp designers' cognitive capacity with "insoluble levels of complexity" (Alexander, 1964, p. 3). Particularly vexing for some beginning designers is that there is no single right answer to the vast majority of design challenges. Multiple viable solutions are the norm for ill-defined design tasks in part because "designers exercise the freedom to change goals and constraints" (Cross, 2001a, p. 82), where each of many framings of a design problem can have its own optimal solution.

More experienced novice and expert designers approach these problems differently. Some experts first aim to understand the challenge (Rowland, 1992; Akin & Lin, 1996) by using "knowledge development strategies" to build rich representations of the unfamiliar challenge (Larkin, McDermott, Simon, & Simon, 1980). They attempt to identify key issues associated with the problem, while scrupulously avoiding making any early design decisions. Others do their initial explorations of a problem by posing a number of possible solutions. Both approaches involve problem structuring (Goel & Pirolli, 1992), in contrast to problem solving, and involve iteratively formulating and framing the problem (Adams et al., 2003), exercising a considerable level of freedom in order to explore all the facets of the challenge (Daly, Adams, & Bodner, 2012), and avoiding making final design decisions too early. Research of large-scale engineering projects, for example, has shown that postponing design decisions reduces the amount of redesign work needed to accommodate unanticipated changes (Gil, Tommelein, & Beckman, 2004). More generally, those whom Bereiter and Scardamalia (1993) refer to as "effective learners" know that identifying what is important in a problem can be hard to discern at the outset, and resist making decisions too quickly about problems, especially in unfamiliar domains, until more is known (Bruer, 1993).

Teaching strategies Educators have devised a number of ways to address the beginning designer's tendency to interpret design problems too simply, frame the problem superficially, and make design decisions prematurely or treat design as a task of well-defined rather than ill-defined problem solving. As shown in the paragraphs below, approaches include having students produce functional descriptions of products before building prototypes, delaying decision making, and helping students do effective problem scoping.

Comprehending the problem statement Before students start even the most preliminary work on a design task, they should provide evidence of comprehending the design challenge's problem statement, often referred to as a *design brief*. Many design curricula ask students to review the design brief and summarize in their own words its key points: the context of the problem, its main goals, and the key criteria and constraints of the challenge. Working within constraints while trying to achieve desired product behaviors is a "big idea" in design thinking (NAE, 2010) for all grade levels (ITEA, 2000).

Functional descriptions One way to restrain students from making premature design decisions is to ask them to generate a functional description of what a viable solution should do to be successful. Such descriptions can be reviewed periodically as students become more familiar with the system they are developing and how to best frame the challenge they face. This approach supports the function-behavior-structure design process model proposed by Gero and Kannengiesser (2004). Taking an integrated approach to linking what a solution needs to achieve (function) with how it is used (behavior) and the form it takes (structure) is an important attribute of design capability and measure of effective designing. For example, Turns (1998) noted in one study that senior undergraduate engineers who produced high-quality designs discussed functional features of their ideas rather than structural features early in their design process.

Problem framing and scoping Probably the greatest reason experienced designers delay design decision making is their appreciation of the benefits of effective problem framing and scoping. Simple comprehension of the task is not enough. They understand at the outset of their work that a design problem's most critical issues must still be discovered and identified before they can be solved. This involves reviewing and elaborating on elements of the problem (Adams & Atman, 2000), identifying and stating user needs, and articulating implicit assumptions during initial problem framing efforts (Bursic & Atman, 1997, p. 66). Teachers can stimulate "coupled iterations" – iterations that integrate problem and solution decisions (Adams et al., 2003) – by explicitly asking students early in the design process about how qualities of their proposed solutions relate to their understanding of the problem. They can then encourage students to review their initial framing assumptions, and update their understanding of the problem as their proposed solutions evolve through multiple iterations. Some curricula prompt students to review problem specifications that they had previously summarized and to answer questions they had raised during earlier efforts at addressing the design problem (Puntambekar & Kolodner, 2005).

Matrix Pattern B. Skipping vs. Doing Research

The Strategy of Building Knowledge through Research Beginning designers *skip doing research in favor of generating solutions immediately.* Informed designers *instead do research on users, write product histories, and collect information on manufacturing methods, materials, and product standards to build understandings of the problem and potential solutions.*

Start-from-scratch design challenges are among the hardest of design tasks for beginning designers to address. Beginners, facing an open-ended design challenge with a blank sheet of paper and few relevant cases or design heuristics in mind, are forced to make one mystifying decision after another. For expert designers, such a task would involve making many design choices that are *routine*, with only a handful of more difficult *novel* problems interspersed among them (Akin & Lin, 1996, p. 42). The working memory of beginning designers can become overwhelmed when they encounter a dauntingly high ratio of novel to routine design decisions. Just as informed designers know when to delay design decisions and why (Pattern A), they also know that doing research can make such a ratio more manageable and help them make more informed design decisions.

When facing well-defined problems, students typically do not look for outside help before attempting a solution (Woods & Crowe, 1984). They can thus skip doing research on the problem, in favor of proceeding directly to generating solutions. In a comparative study of second- and fourth-year industrial design undergraduates, students were asked to redesign a litter system for a train. The less experienced designers would "solve a simple problem; that is, they ignore a lot of the complications in the assignment" and were more likely to produce "sparse problem prototypes organized by superficial features," in part because they "don't even realize they lack information" (Christiaans & Dorst, 1992, p. 132).

One of the major headaches and banes of design instructors is students doing poorly structured and incomplete searches while designing. Beginners sometimes replace research with "found-object designing" (W. Flowers, personal communication, 2006), where nearby objects act as the main source of inspiration for design solutions. While at times yielding creative and effective solutions serendipitously (Wills & Kolodner, 1994), such a search method is considered by some to be neither methodical nor thorough.

Designers need both domain-specific knowledge and situation-relevant strategies to design effectively. Acquiring information is integral to achieving such understandings (Ennis & Gyeszly, 1991; Molina, Al-Ashaab, Ellis, Younger, & Bell, 1995; Wild & McMahon, 2010). Supporting students in doing this kind of work is key to helping them become informed designers. In one comparative study involving freshman and senior undergraduate engineers, seniors who produced products of higher quality made more and varied information requests while designing (Bursic & Atman, 1997, p. 62). A similar trend was noted when professional engineering designers were compared with senior undergraduate engineering students doing the same task (Atman et al. 2007).

Research can help designers change their focus or reframe a design problem, enrich their representation of the problem in their minds, clarify relevant underlying principles, as well as uncover clues to potential solutions. Research can involve working creatively with "conceptual artifacts – such as theories, problem formations and interpretations" (Bereiter & Scardamalia, 2006, p. 700) and can yield ideas that help refute proposed design ideas (Broadbent, 1984). It can also confirm designers' "private frames of reference" that "prestructure their views of the problem" and can help them "keep control of the design process" (Powell, 1987, pp. 193–194). Bursick and Atman's study (1997, p. 68) described how certain student designers may not use information they gather when making their design choices, which suggests that what gets learned through research, like other forms of learning, can become inert (Whitehead, 1929; Bransford et al., 1989).

Experienced designers do much of their research during early designing, when they generate concepts and design ideas (Christiaans & Dorst, 1992, p. 135); however, the need to do research can arise at almost any point in design work. These searches can help in reviewing relevant product standards, finding instances of products for possible reuse (Visser, 1995) or as potential exemplars (Rhodes, 1998, p. 134), and analyzing user preferences (Christianns & Dorst, 1992, p. 135). Research can help in determining methods of manufacture (Barlex & Wright, 1998, p. 160) and construction (Kuffner & Ullman, 1990), provide details on materials' physical specifications and costs (Bursic & Atman, 1997), and show how products work and why they are designed as they are (Kuffner & Ullman, 1990). It can support investigations into constraints and performance parameters of possible solutions (Ennis & Gyeszly, 1991) and help in articulating issues of safety, legal liabilities, and maintenance (Bursic & Atman, 1997, p. 70). Information searches, especially when done using online tools, can involve large quantities of ill-structured information that must be processed quickly (Baya & Leifer, 1994).

Studies have shown, however, that information searches are sometimes conducted as a delaying tactic when groups have reached an impasse (Brereton et al., 1996, p. 334). Less skillful designers in another study performed searches that were "not organized according to some intention" (Christiaans & Dorst, 1992, p. 135), while subjects in the same study who proposed higher quality solutions did more numerous information searches that took less time to complete (p. 135). Atman et al. (1999) observed a similar pattern among certain engineering freshmen who spent considerable amounts of time gathering information, but left little time to make actual design decisions.

Teaching strategies Curriculum developers and design educators have developed different ways to support students in exploring and doing research that informs their design work. These include:

Focused information searches Beginning designers regularly conduct fruitless information searches; in some cases, their queries fail to fit the formal categories used by engineering databases (Kimbell, 1994). Teachers can model for students the use of appropriate search terms and emphasize how the discriminating and strategic evaluation of potential sources for yielding useful data can help. Periodically reviewing the design brief can constrain and curtail runaway information search efforts (Rhodes, 1998, p. 137) and keep students' research efforts more focused (Barlex & Wright, 1998, p. 165). Having students submit a "results table" at regular intervals where search terms and results are gathered and itemized can provide feedback and formative assessment data for teachers so that they can adjust instruction while assessing student progress.

Studying prior art Beginning designers can gain much by researching relevant prior art or "handling collections" (Stables & Rogers, 2001; Kimbell & Stables, 2008) of devices or systems whose functions approximate requirements noted in the design brief. Expert designers who do not want to "reinvent the state of the art if it already exists" favor this approach (Cross & Cross, 1998, p. 144), and take the position that "much everyday design work entails the use of precedents or previous exemplars . . . because the exemplars actually contain knowledge of what the product should be" (Cross, 1999). Benenson and Neujahr's *Stuff That Works!* curriculum (2002) asks upper elementary students to conduct a scavenger hunt in their shopping-bag design task. Students collect and bring to class a wide range of types of bags that exhibit different uses of materials, handle designs, and joining and reinforcement methods. Students in teams group the bags according to criteria of their own choosing, test the bags by loading them until they fail, and then conduct a post mortem to determine the bags' strengths and weaknesses before they design their own shopping bag using a brown-paper lunch bag, string, tape, and other materials.

Writing a product history report Students can do meaningful research when they write a product history of a device or system (e.g., espresso machine, power drill, or audio recorder). Such a paper might describe how the selected product works, the context of its development (country or company of origin), historical era, and milestones in the product's evolution. The inclusion of a product timeline could highlight the advent of new manufacturing methods or materials or detail a product's reconceptualization based on changing user needs or market trends.

Researching users By doing research on a product's customers, beginning designers can build their own mental model of the user. The PIES instructional model (Barlex, 2004) asks students to investigate and write about the physical, intellectual, emotional, and social needs of users. Urban and Hauser (1993) describe a range of social science techniques including user observations, surveys, interviews, and focus group meetings based on more comprehensive methods used in industry. Instructional designers using the ADDIE model (Smith & Ragan, 2005) perform a needs assessment when developing a profile of potential users. Ullman's quality function deployment method (1997) relies on surveys, focus groups, and observations of customers to determine what various users want regarding product features and quality. Role-playing activities can also yield insights about users as well – including feigning injury to investigate the quality of care in an emergency room (Brown, 2009, p. 50), wearing glasses smeared with petroleum jelly to mimic the experiences of the visually impaired, or wearing gloves when using kitchen devices to experience first-hand the challenges the arthritis-sufferers face.

Product dissections and reverse engineering Building a foundation of kinesthetic and haptic experiences with materials and devices is seen as critical preparation for doing scientific inquiry (Woolnough, 1991), science-based design (Zubrowski, 2009), and engineering-oriented visualization (Scriber & Anderson, 2005). Sheppard and Jenison (1997, p. 251) had engineering undergraduates build their own experiential base by conducting product dissections, also known as product teardowns (Sandborn, Myers, Barron, & McCarthy, 2009). With dissections, students are given time to investigate and use the devices before taking apart and re-assembling them using simple tools. They then describe how the devices function, make associations and analogies to similar devices, predict the make-up of unseen subsystems, discuss manufacturing and assembly methods and costs, and identify science and engineering concepts related to the artifacts and how they work. Otto and Wood (1998) detail similar steps when describing a reverse engineering and redesign methodology, and provide details on numerous strategies used in industry that undergraduates also learn to do, including writing 'black box' product function descriptions, conducting customer needs analysis, making various predictions, and performing experiments on key components and the overall product. A recent study found significant pre-post differences in students' understanding of system interconnectivity and abilities to describe reasonable redesign solutions after doing a scaffolded design dissection activity (Dalrymple, Sears, & Evangelou, 2010).

Case-based reasoning with catastrophic and other examples Another approach to doing research involves using case-based reasoning (Kolodner, 1994), which can come into play when students read real-world case studies and, as Lundeberg argues, may make ideas easier to recall because stories help learners organize and store information (NRC, 2011, p. 30). Case stories about designing may involve individuals or entire firms and can highlight various aspects of design thinking that resulted in successful enterprises. However, insights into good design practice can be especially memorable for students when constructed from instances of failed solutions (Bursic & Atman, 1997, pp. 70–71) and from catastrophic failure cases in engineering (Rendond-Herrero, 1993; Petroski, 1993; Pietroforte, 1998). Using cases that represent disruptive innovations may also enable counterintuitive thinking (Garcia, Sinfield, Yaday, & Adams, 2012) that leads to achieving creative breakthroughs to problems.

Matrix Pattern C. Idea Scarcity vs. Idea Fluency

THE STRATEGY OF GENERATING IDEAS Beginning designers *can start their design work with very few or even just one idea, which they may not want to discard, add to, or revise.* Informed designers *want to design with an abundance of ideas and practice idea fluency using techniques such as brainstorming and divergent thinking to explore the design space and at least initially seek to avoid favoring any single solution.*

To address a design challenge, designers need ideas, lots of ideas, and the wider the range of ideas, the better. Sometimes, ideas are in short supply. Idea scarcity can arise from designers' "reluctance to spend the time and mental effort needed to conjure up a rich storehouse of alternatives from which to choose" (Adams, 1986) or from a propensity to shun novelty.

Like many other complex problem-solving enterprises, design is rarely a smooth flowing series of procedures and events that move seamlessly from insightful ideas to inspired prototypes to widely adopted products. At times, the pathway is blocked. Such "stuckness in design" (Sachs, 1999) can arise from procrastination or poor scheduling (Hayes, 1989, p. 331), or what has been called "functional fixedness" by some and "psychological inertia" by others (Otto & Wood, 1998, p. 229). Idea fixation – which "deals with both the inability of designers to see new ways of using objects they are exposed to and the inability to present the use of attributes of an object whether appropriate or not" (Gero, 2011) – can happen to individuals, teams, whole firms (especially large ones), and to entire industries. It has also been noted in both experimental studies and classroom-based research with problem solvers in many fields (Cross, 2000). While idea fixation may not be experienced in the same way across different disciplines (Purcell & Gero, 1996), and may have divergent and overlapping causes which fit that label, it is pervasive across different design domains and persists despite warnings from teachers and consultants.

The situation can be more problematic for beginners, since they may not recognize signals that their work has come to a halt: they may then fail to enact strategies for getting unstuck in a timely way. Beginning designers are not aware of the impact that the invisible yoke of unstated givens or spurious constraints (Akin & Akin, 1996) may have on the questions they ask or the solution vectors they explore. Many designers, particularly novices, find it challenging to think divergently and get trapped by characteristics of known solutions (Daly et al., 2011). Some beginning designers work "depth-first" (Cross, 2000) and spend too much time developing a single idea, which may result in limited project time getting used up and first plans being implemented out of sheer necessity.

Numerous explanations have been put forward to account for idea fixation, as it is an issue found in many areas of problem solving. Studies from cognitive science suggest that limits of short-term and working memory can contribute to design fixation, despite a subject's willingness to seek other alternatives (Smith, 1995; Kohn & Smith, 2009). From a situated cognition perspective, designers' thinking can become fixedly contextualized within the boundaries and unquestioned assumptions that arise during problem framing (Cross, 2001a), when designers can "strongly pre-structure their views of problems" (Powell, 1987, p. 193). Curriculum or instructor pedagogy may also be a contributing factor. Early cues or hints from the teacher or illustrations in instructional materials could lead students to favor some solutions over others. This could result in fixation by novice and expert designers alike (Jansson & Smith, 1991; Linsey & Viswanathan, 2010), although this trend was found to be less prevalent in one study involving senior undergraduate industrial designers (Purcell & Gero, 1996). Seen through a constructive-developmental lens, designers may become embedded in and subject to (Kegan, 1982) their initial design plans, a psychological dynamic that would render certain designers less able to reflect objectively upon their proposed ideas. Crismond (1997) noted how expert designers were well practiced at generating one idea after another and were able to set aside each idea in turn, in a deliberate act of letting that idea go, so that they could make a fresh start at proposing yet another qualitatively different approach.

Teaching strategies Effective idea fluency should help designers both explore and expand the design space in which they are working. One psychometric tool for measuring the products of idea generation focuses on four features that any collection of design ideas should contain: novelty, variety, quality, and quantity of ideas (Shah & Vargas-Hernandez, 2002). Recent research has used these metrics to study the effectiveness of certain intuitive ideation methods to produce collections of design ideas (Vargas-Hernandez, Shah, & Smith, 2010). A concise review of the different types of approaches for generating many design ideas can be found in Shah and Vargas-Hernandez (2002, p. 112). These approaches include provocative stimuli (exposure to new concepts), suspended judgment, flexible representations (collaborative sketching), changing the frame of reference for seeing the problem, incubation, and exposure to example ideas (Shah, Smith, Vargas-Hernandez, Gerkens, & Wulan, 2003).

Divergent thinking Techniques to help people achieve divergent thinking have been proposed in various guises and have been described in books that catalog heuristics for helping people achieve idea fluency through creativity. Among classics in this field are Adams's *Conceptual Blockbusting* (1986), de Bono's *Lateral Thinking* (1970), Hayes's *The Complete Problem Solver* (1989), and McKim's *Experiences in Visual Thinking* (1980). Techniques presented in these books include delimiting and proposing alternative views of the problem, doing idea sketching and visual recall, incubating ideas by stopping work on a problem for a while, and generating personal and direct analogies.

To help designers explore the space of possible design solutions and facilitate the discovery of novel concepts, Daly et al. (2011) developed an empirically based set of design ideation strategies (Yilmaz & Seifert, 2011; Daly et al., 2010) called Design Heuristics. Each heuristic appears on one of 77 strategy cards and suggests a different strategy (e.g., convert for second function, utilize opposite surface, nest, and use alternate energy source) to use for generating ideas. Each card offers an action prompt, an abstract image to represent the strategy, and two examples that show the application of the heuristic to existing consumer products. For example, the *Utilize opposite surface* card shows two examples: an athletic shoe where the laces wrap around toward the bottom of the shoe to allow better mobility and a dining chair where the back side is shown to reveal additional storage options. These divergent thinking strategies were tested in an undergraduate engineering course, where 48 students were provided with a short information session on the use of the Design Heuristics, followed by a 25-minute idea generation session and a 20-minute design debrief session. An analysis of concepts students generated indicates that the Design Heuristics facilitated exploration of the design space, which includes more original and more diverse ideas.

Brainstorming One of the hallmark strategies of designers, brainstorming, involves generating a wide-ranging collection of ideas while deliberately withholding criticisms and deferring judgment on the quality of those ideas. Ideas may be generated using a wide range of materials and modes of expression such as sketching, which is linked with the reinterpretation of design ideas (Gero, 1999). Making analogies can encourage grouping and connecting ideas in unexpected ways, which may enhance ideation (Ulrich & Eppinger, 1995; Ball & Christensen, 2009; Stacey, Eckert, & Earl, 2009) and lead to the development of new products (Perkins, 1997). Kimble and Sables (2007) and Johannson (2006) note research that supports having designers first brainstorm individually and then share their ideas with others.

Research has suggested that instructions emphasizing the withholding of criticism are less effective than stressing the creation of large numbers of ideas in producing more ideas and more good ideas (Paulus, Kohn, & Arditti, 2011). However, simply asking students to generate lots of ideas with or without judging them ignores the nontrivial challenge of developing an ability to brainstorm. Without scaffolding, elementary and middle school student designers often do not generate multiple solutions when facing design problems (Welch, 1998; Welch, Barlex, & Lim, 2000). Attempts to mandate idea fluency have backfired on teachers, especially when such edicts are issued without explaining to students the reasons for such a dictate. McCormick, Murphy, and Davidson (1994) describe cases where teachers required students to include three or four candidate ideas in their design portfolios, from which students purportedly would select one idea for implementation. The authors tell how students actually generated the requisite alterative solutions after completing their design projects that were based on a single idea. They referred to such student portfolio work as a "veneer of accomplishment." When, without rationale, brainstorming is proposed for students to do, they can treat it as a required classroom ritual that they perform superficially, if at all.

Constraint relaxation and "dream designing" At certain junctures in a design project, expert designers may opt for a time to set aside all limitations – including those imposed by nature, the design brief, or the client – in order to propose solutions from a fresh perspective. When asked about such "dream designing" during a post-design interview (Crismond, 1997), one MIT design professor noted, "At some point in the design process . . . you just forget about constraints and imagine the thing you are designing in an ideal world, where limitations like cost and material are not an object." Practitioners do "constraint relaxation" (Moorman & Ram, 1994) in an attempt to decouple the design task from the circumscribed contexts in which their initial thinking has taken place, with the aim of harvesting a new crop of ideas that they would not have thought of otherwise. Later, they then adapt them so that they eventually address the constraints of the original problem specifications.

Generative database searches Searching trade magazines, journals, and databases can help designers generate new product ideas (Ulrich & Eppinger, 1995, p. 86; Ullman, 1997, p. 141), although such approaches can be unproductive for beginning designers (Radcliffe & Lee, 1989, p. 206). Students can benefit from reviewing collections of relevant design elements that can be found in classic works that illustrate the broad range of mechanical elements developed over the centuries (Jones, 1930) or books that showcase specialty collections of different paper mechanisms and folding techniques for making pop-up books (Carter & Diaz, 1999). The Invention Machine software (Derringer, 1996) uses a case-based reasoning AI engine that is linked to the U.S. Patent Office's database and aims to help designers make unexpected yet generative connections and approaches during conceptual design and hence reduce the likelihood of idea fixation.

Starter vs. final project challenges Design challenges can be structured so that students are less prone to idea fixation. One such pedagogical approach involves presenting students with a starter challenge and then later modifying either the materials used for fabrication (Zubrowski, 2009, p. 326) or changing the task specifications for the final design task itself. In a cardboard chair design challenge (Goldman, 2002), for example, students were asked first to build two or three qualitatively different miniature chair prototypes out of index cards. They were then given two 4-by-8-foot cardboard sheets and asked to produce, without using glue, fasteners, or tape, a quarter-, half-, and finally full-scale cardboard chair that could support a 150-pound person sitting and leaning back in it. This instructional sequence can prevent students from fixating on their initial design ideas, because by changing the scale of the prototype, the materials that can be used to make it, or the specifications themselves, students are forced to make fundamental revisions to their ideas in the face of design challenge requirements that keep evolving.

Matrix Pattern D. Surface vs. Deep Drawing and Modeling

THE STRATEGY OF REPRESENTING IDEAS FOR DEEP INQUIRY Beginning designers *propose and sketch ideas that superficially resemble viable solutions but that do not support deep inquiry into how a solution might function, and would not work if built.* Informed designers *use gestures, words, and artifacts to explore and communicate their design plans. They make drawings, construct physical prototypes, and create virtual models that help them develop deeper understandings of how their designs function.*

Beginning designers can produce ideas and sketches that emphasize superficial aspects of potential solutions, ones that lack crucial specifics necessary for their ideas to work when built, and that do not contribute to conducting meaningful investigation into those ideas. They ignore constraints and produce "ideation without substance" (Newstetter & McCracken, 2001), spend little time doing preliminary design drawings (Welch, 1998), and make scant use of such drawings later when making prototypes (Gustafson, MacDonald, & Gentilini, 2007). Beginning designers may produce no drawings or faulty ones because they lack the requisite graphic fluency (Fleer, 2000) in sketching, which "requires considerable skill" (Welch et al., 2000, p. 141). They have patchy or inaccurate device knowledge (Johnson, 1988; McCormick, 1994), ignore constraints, and create proposals that could not be realized as actual products (Newstetter & McCracken, 2001, p. 67). When operating with little functional knowledge of the device, they can generate plans that focus "almost entirely on aesthetic features" (Fortus et al., 2004, p. 1097). Miller (1995) studied teams of three or four MIT undergraduate designers doing single-session, materials-constrained design challenges where they created models of cranes and mechanical triggers. Videotapes of these sessions showed students "building nonfunctional imitations of known devices" (Miller, 1995, p. 15) and making "pre-Archimedean" errors where "the preponderant overall form of mistake was to build a design visually resembling some relevant generic device, but lacking functional connections or relationships among its parts." Students were unable to "form competent analytical models of whatever physical objects" they were designing, which required "applying basic physical knowledge to concrete design-and-build problems" (Miller, 1995, p. 14).

For graphically literate designers, sketching can support visual reasoning and design thinking in a number of ways by (1) making internal thinking about aesthetics, ergonomics, and mechanics explicit; (2) extending short-term memory so that more complex systems can be envisioned; (3) enabling problem scoping and solution archiving by enhancing collaboration and communication; and (4) supporting the designers' own dialogs with ideas and their evaluation of imagined solutions (Archer, 1979; Ullman, Wood, & Craig, 1990; Suwa & Tversky, 1997; Heiser, Tversky, & Silverman, 2004; Cardella, Atman, & Adams, 2006; Goldschmidt, 1991). The inherent ambiguity of sketches can invite designers to explore new directions when designing (Garner, 1989; Fish & Scrivener, 1990). Sketches of imagined products sometimes act as drawing experiments that allow designers "to test a hypothesis, explore phenomena, and affirm or negate the move" (Schön, 1984).

In design work, modeling can involve building a physical prototype – "an approximation of the product along one or more dimensions of interest" (Ulrich & Eppinger, 1995, p. 219) – using easy-to-fabricate modeling materials, like cardboard and duct tape, or easy-to-assemble structural elements, like LEGOs™. Mathematical models, including those that are the basis of computer simulations, can represent the problem or potential solutions and act as cognitive devices to enable thinking (see Visser, 2006). These approaches can help students visualize their product ideas more easily, especially those with modest drawing skills (Lemons, Carberry, Swan, & Rogers, 2010), and are viewed by many engineering educators and researchers as core competencies of effective design practices (ITEA, 2000).

Teaching strategies Beginning designers' inability to represent their design ideas accurately or with sufficient detail can contribute to the superficial designs they produce. Extended instruction in sketching has been proposed (MacDonald & Gustafson, 2004) to help establish graphical thinking and literacy as a "profound and diverse resource" for students to use "at the very earliest conceptual stages and as a final act in the design process" (Garner, 1989, p. 43). The following are some strategies that address deficiencies in sketching and drawing and introduce various forms of modeling to enhance design thinking.

Messing about with given models David Hawkins coined the term "messing about" (2002) to describe a form of careful observation and hands-on investigation of materials that precedes a child's more formal scientific investigations. The technological equivalent of messing about in design appears in curricula such as *Learning by Design™* (Kolodner, Crismond, Gray, Holbrook, & Puntembakar, 1998; Kolodner et al., 2003) and *Project-Based Inquiry Science* (Georgia Tech Research Corp. [GTRC], 2010), where students are given materials and plans for building and then exploring initial prototypes. Sadler, Coyle, and Schwartz (2000) describe ways to support students' modest design skills and background knowledge by providing them with plans for a barely working yet functional prototype, which they then build, test, and improve upon through iterative redesign. Having beginning designers fabricate flawed yet working models provides them with an initial taste of success, yet leaves them plenty of room to improve their devices over multiple iterations. The instructional sequence described in Zubrowski's standard model (2002a) has students first design an initial prototype without suggestions or help from the instructor, and then build a teacher-supplied model of the same device. After testing both models, students attempt to synthesize ideas to create an optimal solution. Goldsmith College's Richard Kimbell tells how students do the physical equivalent of brainstorming when they rapidly fabricate small-scale prototypes from easy-to-use materials, which he calls "conceptual making" (Georgia Tech Research Corp., 2004a). All of these instructional techniques guide beginning designers to explore the design problem space using a "solution-focused" approach (Lawson, 1979), support them in engaging in dialogs with the materials they fabricate and use (Bamberger & Schön, 1983), and help them conduct exploratory discussions and investigations that may make a problem more tractable (Kavakli & Gero, 2003).

Building before sketching Many instructors ask beginning designers to follow a sequence for concept development that expert designers often use: first envision, then sketch, and then build a model (Constable, 1994; Egan, 1999). Some younger designers prefer to sidestep sketching in favor of immediately creating a physical model when designing (Welch et al., 2000), in part because of a preconception they hold that says all drawings must be presentable renderings of finished products (Constable, 1994). Since students make better sketches after they have seen artifacts similar to their envisioned prototypes or have such items in hand (Anning, 1997), the standard sketch-then-make sequence might well be reversed. A study involving eight undergraduate engineering students found that doing modeling first with an open-ended design task enhanced students' visualization of problem solutions and improved their understanding of how the prototypes worked without requiring additional time to complete their design projects (Lemons et al., 2010).

Virtual drawing and computational modeling Computer-aided design (CAD) software, including low- or no-cost programs such as Google *Sketchup*, can enable students to create and consider details of design plans prior to building prototypes (Crismond, Howland, & Jonassen, 2011). The use of such systems can aid students' visualization of plans and has long been an important goal for undergraduate engineering students (Committee on Engineering Design, 1961) and for those in middle and high school settings (Cline & Mandinach, 2000). Computer-based simulation and systems modeling programs such as STELLA (Mandinach & Cline, 1996) can scaffold students' engineering knowledge and estimation skills, and enable them to make first-order approximations of a model's performance in the early phases of designing. These approaches, however, carry potential drawbacks. The precision required in creating CAD drawings (e.g., explicit dimensions and shapes) runs counter to the kinds of ambiguity in rough sketches that sometimes provoke novel visual relationships (Goldschmidt, 1991) and promote divergent thinking (Fish & Scrivener, 1990). These tools also carry with them their own learning curves and cognitive demands, which can impede students' causal reasoning about how the products worked, and their ability to identify problems and communicate effectively about issues with their designs (Kimbell & Stables, 2008, pp. 203–205).

Descriptions and structured reviews of design ideas Research has shown that both professional and student designers use verbal descriptions more frequently and in more critically useful ways when communicating early design ideas than by freehand sketching or computer-aided drawing (Jonson, 2005). Verbal statements can be more effective than sketching in supporting designers' explorations of evolving ideas and may be the most powerful strategy teachers can recommend for helping students with meager sketching capabilities. Periodic, structured conversations where students have small-group peer review discussions can help advance students' design ideas (Kimbell, 2004, p. 137). One such format developed by Kimbell, Stables, and Green (1996, p. 14) had a significant impact on the direction of students' early design thinking and work, and involved each member of a design team giving a two-minute update to the rest of the group on her or his current project thinking, including what had been recently accomplished and why. The short presentation ended with what would be done next, after which the rest of the students gave feedback to the presenter.

Artifacts and gestures as stand-ins for drawings Harrison and Minneman (1996) describe how experienced designers used nearby objects as props when discussing their designs ideas. Hand gestures may act as stand-ins for objects or drawings and may help direct the attention of others during design conversations (Heiser et al., 2004; Visser, 2009). Using and making reference to physical prototypes can help clarify and stabilize meaning making among designers, while supporting the integration of relevant concepts with these artifacts (Roth, 1995b). Such strategies, which Logan and Radcliffe (1998) called "artefacting," may help design team members from different disciplines communicate better with one another.

Matrix Pattern E. Ignore vs. Balance Benefits and Trade-offs

THE STRATEGY OF WEIGHING OPTIONS AND MAKING DECISIONS Beginning designers *ignore or pay too little attention to design criteria and constraints, and focus only on positive or negative aspects of their design ideas without thinking of associated benefits and trade-offs.* Informed designers *balance systems of benefits and trade-offs when they consider various plans, make design decisions, and justify them.*

Design is a special kind of problem solving that is honeycombed – start to finish – with decision points that require making dozens, even hundreds, of choices (Akin & Lin, 1996, p. 55; Strobel & Pan, 2011). Reasoning about the benefits and trade-offs of different design alternatives is a cornerstone of design thinking and decision making (ITEA, 2000) and is needed for designers to resolve conflicts among a plurality of objectives when designing (Rittel & Webber, 1984; Jonassen, Strobel, & Lee, 2006). Nelson and Stolterman (2003) describe the link between intention and judgment as a hallmark of "the design way." Decisions abound as designers move from one problem to the next, including picking the best material for fabrication, selecting from among a range of manufacturing methods, and choosing among conflicting demands of different users' needs. In the earlier phases of designing, qualitative judgments about which solution pathways to pursue or pass over can be made quite quickly – sometimes based on back-of-the-envelop calculations or estimations (Linder & Flowers, 2001), the invocation of practice-based guidelines (Brand, 1994, p. 135), and patterns or "rules of thumb" (Alexander, 1979, p. 179).

Beginning designers can be oblivious to the unavoidable tensions and trade-offs associated with design. Their decisions may be made based on criteria that are unstated, inchoate, or in flux. When asked to describe their design decisions, they may tell only of the benefits of their preferred design choices, while neglecting to mention associated trade-offs. They likewise may highlight the negative aspects of less favored approaches while passing over potential benefits. They may apply guidelines for making design decisions without critically examining their applicability to the problem at hand (Goldstein & Hogarth, 1997, p. 13). Informed designers, on the other hand, are practiced at weighing and articulating both the positive features and drawbacks of ideas that they are about to select or reject and look for potential downsides even with the most promising ideas.

Skill theory (Fischer, 1980, 2006) describes development using cognitive structures called skills and rules for transforming those skills through increasing levels of complexity. Skill theory and its terminology can be used to describe how designers develop increasingly complex ways of reasoning about benefits and trade-offs when making design decisions. When beginning designers propose a new feature or product idea, they initially would focus only on the positive [P] or negative [N] aspects of that idea but not both. Each amounts to a separate, single representation set of that design idea, [P] or [N] (Fischer, 1980, p. 490; Fischer & Bidell, 1998). A more complex way of thinking of the design idea would involve coordinating or mapping the positive and negative features for that design [P – N]. As more design ideas get considered and the strengths and weaknesses of each get identified and analyzed, a system composed of those ideas can form [A^P_N – B^P_N – C^P_N], making decision making among design options more thorough and thus informed. Until students can coordinate the benefits and trade-offs of design ideas they are considering, they will need support in doing this aspect of informed design thinking.

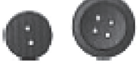
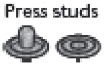
Teaching strategies Research in judgment and decision making suggests two broad approaches for helping people make informed choices, both of which may be applicable when doing design. A reasoning-based approach would support decision makers in using qualitative verbal arguments to articulate rationales for different alternatives they are considering. A second approach involves teachers presenting students with graphic representations of decisions based on formal, value-based models. Such systems quantify alternatives by assigning values and weights to different factors, which are then aggregated to make a final choice (Shafir, Simonson, & Tversky, 1997).

Explanation-based designing With this approach, teachers scaffold students' thinking about the benefits and trade-offs of different design options by regularly asking them to provide explanations for their design decisions, including description of both the positives and negatives of different choices. Students can also use experiment-based design advice or science and engineering principles to explain and support decisions they have made. McKenna, Linsenmeier, and Glucksberg (2008) found that student designers in a senior capstone course were more likely to support their design decisions with explanations based on computational and analytical evidence than were students in a freshman design course.

Decision diagrams In the Nuffield Design and Technology curricula, the Chooser Chart is a highly visual and iconic rendering of a standard decision matrix (Barlex & Givens, 1995, p. 50; see Figure 2). The chart supports students' design thinking by representing and aggregating the full range of design alternatives, with each option (row) scored using one to four bullets for each of the criteria noted at the top of the chart's columns. Students arrive at a design decision regarding what option to use either by totaling the number of bullets for the criteria they have selected as high priority or by simply eye-balling the chart for the optimal collection of bullets. Students can also be asked to create their own chooser charts, based on research and tests they conduct.

The House of Quality diagram (Figure 3) is among a number of sophisticated decision matrices that help designers translate user needs and preferences into measurable product performance outcomes (Hauser & Clausing, 1988). Final design decisions are based on totals of summed weighted or raw scores. Some experienced designers avoid slavishly following the calculated ranking these charts generate, holding that gut-feeling impressions can be just as important for considering product feasibility (Ullman, 1997, p. 155) and making design choices. Despite these differing views, the very act of having students create decision charts or matrices may help them further develop their ideas by articulating priorities and judging anticipated performances for a range of design alternatives.

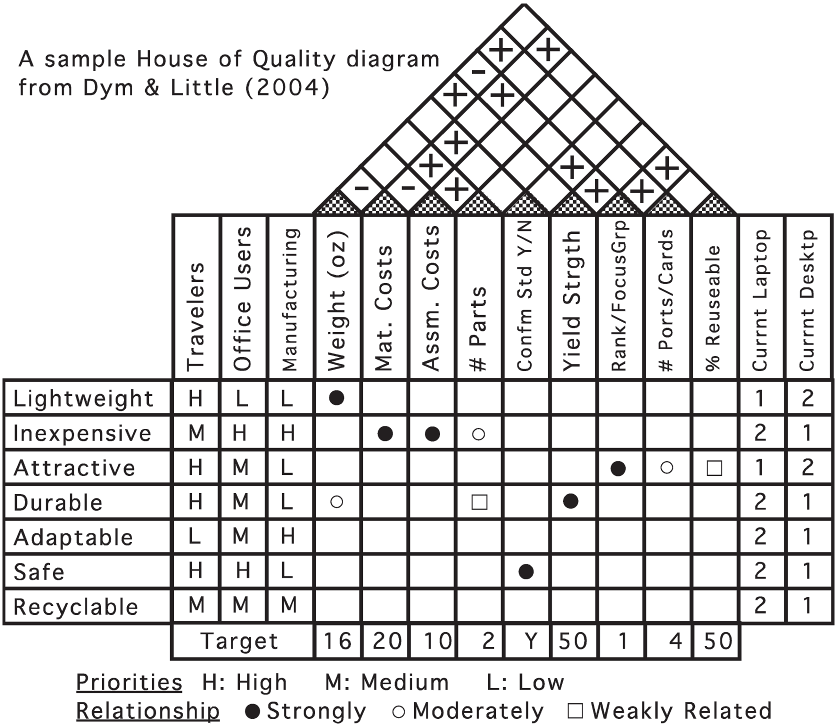
Fastenings Chooser Chart

	Ease of use	*Variety of types*	*Strength*	*Ease of care*	*Cost*
Buttons 	●●	●●●●	●●	●●	▲▲
Zips 	●●●	●●	●●●●	●●	▲▲▲
Velcro 	●●●●	●	●●●●	●●●	▲▲
Hooks/eyes 	●	●●	●	●●●	▲
Press studs 	●●●	●●	●	●●●	▲
Clips/buckles 	●●	●●	●●●	●●●	▲▲▲

● = few blobs for worse, ●●●● = more blobs for better
▲ = cheap, ▲▲▲ = most expensive

FIGURE 2. Nuffield's Fastenings Chooser Chart helps students reason about the competing features of different garment fasteners.

Design values and guidelines Design values permeate and impact designing; they influence both how designers initially perceive and frame the task and how they evaluate ideas and complete their projects (Bucciarelli, 1984). These values can address issues related to product quality, including designing for reliability, manufacture and assembly, and designing for sustainability (McDonough & Braungart, 2002; McLennan, 2004; Ullman, 1997). The human-centered innovation approach, for example, aims to have designs simultaneously meet the needs of desirability, viability, and feasibility (Brown, 2009). Simplicity is another powerful design value relevant to many fields of design, since simpler systems tend to be more robust and reliable than are more complex ones. Trade magazines and books on design admonish both beginning and expert designers to avoid "creeping features" (Ullman, 1997) and "feature creep" (Kemper, 2003), and buttress such advice with



	Travelers	Office Users	Manufacturing	Weight (oz)	Mat. Costs	Assm. Costs	# Parts	Confm Std Y/N	Yield Strgth	Rank/FocusGrp	# Ports/Cards	% Reuseable	Currnt Laptop	Currnt Desktp
Lightweight	H	L	L	●									1	2
Inexpensive	M	H	H		●	●	○						2	1
Attractive	H	M	L							●	○	□	1	2
Durable	H	M	L	○			□		●				2	1
Adaptable	L	M	H										2	1
Safe	H	H	L					●					2	1
Recyclable	M	M	M										2	1
Target				16	20	10	2	Y	50	1	4	50		

FIGURE 3. The House of Quality diagram graphically depicts different user preferences, product features, and their relationships to one another (from Dym & Little, 2004).

descriptions of the dire consequences of creating designs that are overly complicated. Teachers use various forms of the acronym KISS (keep it super simple) to promote elegance, parsimony, and simplicity in their students' design work.

Emotions and their role in design decision making Weighing benefits and trade-offs of various design options is necessary to an informed designer's thinking, but it is not sufficient for making decisions. Findings from cognitive neuroscience studies point to the essential role that emotions play in decision making. In Damasio's study of a brain tumor patient named Eliot (2005), damage during surgery to an area of this person's prefrontal cortex led to his complete loss of emotion, and with it any ability to function with friends, family, and work. People who suffer from such a condition, when asked to make a simple decision such as choosing between two dates for an appointment, are known for spending extended periods of time "enumerating reasons for and against each of the two dates" and conducting "a tiresome cost-benefit analysis, an endless outlining and fruitless comparison of options and possible consequences," yet are incapable of making a choice (Lehrer, 2010).

While a mystique regarding the role intuition plays in an expert's decision making should be avoided (Alexander, 1964, p. 6), incorporating both analytical insights and inclinations for some options over others based on one's feelings should be considered as a teaching strategy when supporting students in their design thinking. In his teaching of the undergraduate and graduate introduction to design courses at MIT, Pappalardo Professor of Mechanical Engineering Woodie Flowers would ask his students – after they had spent time analyzing their design options – a unique and subjective question: "Which idea smells good to you?" This prompt aimed to get students in touch with the feeling side of their engineering thinking and encouraged a productive dialog between rationality and emotions when attempting to make a design decision.

Matrix Pattern F. Confounded vs. Valid Tests and Experiments

THE STRATEGY OF CONDUCTING TESTS AND EXPERIMENTS Beginning designers *run few or no tests on their design prototypes. When they do them, they conduct confounded experiments by changing multiple variables in a single experiment, which yields little understanding about potential solutions.* Informed designers *run valid tests as part of technological investigations that help them to learn quickly about design variables, users, and materials, to understand how things work, and to optimize the performance of the prototypes they decide to develop.*

When the limits of research have been reached and Internet sources have been exhausted, designers must generate their own data through conducting inquiry-based laboratories (Litzinger, Lattuca, Hadgraft, & Newstetter, 2011) where students plan investigations and interpret data they gather to check on their own predictions and possible explanations (hypotheses) of prototype behavior. Professional designers, acutely aware of project deadlines and conscious of time constraints, favor ways of doing tests that generate insights quickly rather than doing more time-consuming approaches that possess greater scientific rigor (Norman, 1996, p. 98). Still, they occasionally do controlled experiments, although they do not run such tests to refute a formal hypothesis, since their results need not be replicated (Cross, 2001b, p. 51).

In most professional settings, the scientific quest to understand *why* runs a distant second to a designer's need to know *what* and *how*. This is far less the case in schools where design activities are being used to support students' learning of STEM concepts (APASE, 1991; Frye, 1997; Kolodner et al., 1998; Sadler et al., 2000; Zubrowski, 2002a; Fortus et al., 2004). Schauble, Klopfer, and Raghavan (1991) distinguish between engineering and science models of experimentation. They suggest that the engineering model aims to "optimize a desired outcome" and can address technical and social dimensions, while the scientific model of experimentation aims to identify causal links between predictor and outcome variables. They consider the engineering model to be more consistent with everyday problem solving and note that it appears in students' behavior before students do well-planned and properly controlled experiments, which is a key goal in the teaching of science, of their prototypes.

Informed designers also use social science methods when conducting informal interviews, administering questionnaires, running focus groups, and observing users interacting with a product. The educational opportunities to reinforce the authentic practice of scientific practices while designing, especially inquiry, have been reported in a review of the use of inquiry-based approaches in engineering education settings (Litzinger et al., 2011, pp. 136–138), and have been incorporated into recently published K–12 curricula and in undergraduate engineering education settings (Sheppard, 2009).

Teaching strategies A number of recently published design-based science curricula (e.g., Project-Based Inquiry Science's *Diving into Science*, GTRC, 2010; Science by Design's *Construct-a-Catapult*, TERC, 2000; Challenges in Physical Science's

Electromagnets, Coyle, 2001) ask students to plan and conduct controlled scientific experiments where they identify a single product feature to vary, fix all other variables, and then determine which product performance outcomes to measure and how (see Harlen, 2001). Such plan-and-investigate tasks can be preceded by students having whiteboarding discussions that build upon the KWL chart (What do you *know*? What do you *want* to know? What did you *learn*?; Ogel, 1986) – where students list facts, ideas, and learning issues related to investigating the impact key design variables have on a system's performance (Kolodner et al., 2003).

The following are types of investigations students can do to build the system and device knowledge they need to address design challenges in an informed way.

Experiment-based design advice Students can use results from tests that they conduct on their prototypes to formulate experiment-based design advice that describes the impact of altering single design variables on a product's performance. Students report these application-ready findings from their tests as design advice, also referred to as *design rules-of-thumb* (Crismond, 2001, p. 796; Crismond, Camp, Ryan, & Kolodner, 2001; Kolodner et al., 2003; Kolodner et al., 2004; Crismond, 2011), to help other classmates with their own design planning and decision making. Such findings act as intermediate abstractions (White & Frederiksen, 1993) that link science ideas and the concrete realities of particular mechanisms and products and how they work.

Investigate-and-redesign task One form of technological investigation is the I&R task sequence (Crismond 1997, 2001), which begins with a *novel design* task (Hawkins, 1990) where students examine unfamiliar devices to try to identify them and describe their functions. In the a*nalyze devices* step, students take multiple instances of the same product and then use physical and engineering science concepts to explain how they work and make predictions about their comparative performances on a given task. In the *ideal feature step*, students list preferred functions of an ideal version of the device while disregarding issues such as cost, feasibility, or customer appeal. They then *plan an experiment* that compares different brands of the device being analyzed, do the *conceptual redesign* of the product, and end by *reflecting* on the processes they used in doing this work.

Product comparisons Conducting a *Consumer Reports*-styled experiment that compares different brands of the device, or product comparison, can build an understanding of key product features and performance behaviors needed to do the informed redesign of a device (Crismond, 2001). Students doing product comparisons can report on how different devices use different approaches to perform the same task and can elaborate on how different user needs and preferences were addressed by different brands of the same device. Such work may also enhance analogical transfer of solutions to the current design problem, while helping students gain insight into science and engineering principles (Loewenstein, Thompson, & Gentner, 1999). For teachers, device selection is critical in devising an effective product comparison activity: the design approaches and performances of candidate items of the same product type need to be sufficiently different to make the comparison interesting to students, while still illuminating key design problems and issues.

Matrix Pattern G. Unfocused vs. Diagnostic Troubleshooting

THE STRATEGY OF TROUBLESHOOTING Beginning designers *have an unfocused, non-analytical way of viewing the plans and performance tests of prototypes when troubleshooting their designs.* Informed designers *focus their attention on* *problematic areas of their potential solutions and products while doing effective diagnostic troubleshooting.*

Some designers will not abandon their design ideas, even after running many tests and design iterations that clearly demonstrate a plan's ineffectiveness. Beginning designers can look uncritically, in a coarse-grained, undifferentiated, and unfocused way, at their plans and prototypes' performances when troubleshooting these designs. They can generate and test hypotheses about them at random (Johnson, 1988), while not actively looking out for worrisome patterns when testing prototype performance. This can result in them seeing and describing as "satisfactory" what an experienced designer would call a "flawed performance." These designs are thus inoculated from change, despite numerous design iterations, and can end up looking strikingly similar to concepts that were proposed from the very beginning.

Design-based troubleshooting shares a number of traits with classical troubleshooting, the latter being a form of moderately ill-defined problem solving that involves an attempt "to isolate fault states in a system and repair or replace the faulty components in order to reinstate the system to normal functioning" (Jonassen & Hung, 2006, p. 26). A competent technician charged with fixing an existing product that is broken possesses conceptual models and skills that include system and device knowledge, appropriate domain knowledge, and awareness of a system's physical layout and topography, as well as knowledge of relevant procedures for troubleshooting the product and testing for potential faults (Jonassen & Hung, 2006). Topographic knowledge (Rasmussen, 1984) involves an understanding of a device's physical structure, which guides practitioners in locating sources of particular problems. Functional knowledge speaks to how the system works and how subsystems and their components interact. Domain knowledge addresses the science and engineering principles that explain the product's basic functions (e.g., Hooke's law for the return spring of a water pistol's trigger; Newton's laws of motion for model car's acceleration). While such ideas and practices alone are not sufficient for effectively diagnosing faults (Jonassen & Hung, 2006; Morris & Rouse, 1985), they can enable practitioners to transfer troubleshooting skills to new settings (MacPherson, 1998), which can also be helpful when troubleshooting an evolving design concept or prototype.

When the process of design-based troubleshooting occurs during conceptual design and the artifact does not yet exist in a testable form, informed designers must run mental simulations of how the envisioned device or system might work. They need to imagine a "sequence of salient events in causal order" (Mioduser, Venezky, & Gong, 1996) in order to make a feasibility judgment and to predict sources of poor product performance (Ullman, 1997; Adams et al., 2003). When testing physical prototypes, design-based troubleshooting involves actively looking for critical events and patterns of behaviors that diverge from this mental model. These harbingers of lackluster performance or abject product failure help to differentiate well-conceived products from those that need tweaking and those plans that should be discarded. When faults or flaws are noticed, observers zoom their attention in and then out when examining the system's performance. Such narrowing and focusing of attention helps practitioners isolate faults by reducing the complexity of the system being considered. This lessens the load on working memory, which in turn can improve troubleshooting performance (Axton, Doverspike, Park, & Barrett, 1997). Informed designers also use case-based reasoning to recognize patterns of current system performance based on similar cases they have encountered and can use causal reasoning to follow anomalous events backwards to one or more root causes, which may reside in the design's conceptualization, construction, or even the designer's testing methodology. Experienced authors use similar processes in revising their compositions (Flowers, Hayes, Carey, Schriver, & Stratman, 1986).

Teaching strategies The role that diagnostic troubleshooting plays in designing is an understudied area of research. It resembles "diagnostic judgment for action" (Rasmussen, 1993), where practitioners search a system for behaviors, components, or subsystems upon which to act, and parallels activities associated with scientific inquiry (Harlen, 2001), including observing, noticing recurrent patterns in data, explaining phenomena, and doing design-based experiments (Pattern F).

Disparities between intended function and actual product behavior during prototype testing that go unnoticed cannot contribute to the iterative improvement of a design. The potential for what students can learn through iterative design gets diminished when students' attention remains diffused and unfocused, and when students fail to notice and attend to critical and problematic features in their designs. The following teaching strategies aim to help students develop their design-based troubleshooting capabilities.

Diagnostic troubleshooting Diagnostic troubleshooting has been practiced and studied as a structured, inquiry-based, four-step procedure (Crismond, 2008; 2011). The first step involves a particular kind of *observing* that entails looking at a product's overall performance during early prototype testing in order to detect unexpected or out-of-range behaviors. The second step involves the actual *diagnosis* of the problem, where the designer gives a name to the problems noticed in the product's performance. Next, an *explanation* of why those behaviors occur is offered, which can help students causally link faulty performance with specific elements of the planned or actual design. The last step, less analytical than the others, involves proposing ways to *remedy* and fix the design or prototype. Detected flaws can inspire ideas for simple fixes, additional features, or entirely new and unimagined systems. A new iteration of the product then gets built and tested, which goes through additional diagnostic troubleshooting cycles as needed. As with scientific discovery, noticing unexpected properties or behaviors during testing can become a powerful impetus for reconceptualizing product criteria and constraints (Wills & Kolodner, 1996).

Cognitive training in troubleshooting The cognitive training model has been used to teach troubleshooting in a range of well- to ill-defined problem settings (Foshay, Silber, & Steinicki, 2003). When used in an instructional context involving design challenges, learning activities could primarily aim to help students build mental models of how the device and its subsystems work. Lessons could review relevant science and engineering principles and present case studies of typical failure modes with their causes and remedies. Procedures for testing and repairing identical devices or analogous systems, as well as basic troubleshooting heuristics, could be taught and practiced using real devices or computer simulations of broken devices or systems (Jonassen & Hung, 2006).

Troubleshooting stations Setting up separate activity stations, each with a device that possesses a noticeable flaw that needs troubleshooting, can engage students in developing (while helping assess) troubleshooting capabilities. Zubrowski produced a collection of videos (EDC, 1999) that shows fourth grade students who were engaged in a model windmill design activity visiting each of four troubleshooting stations. At each table, students found a different windmill prototype with a significant design or fabrication flaw that made it perform very poorly or not at all. Students were asked to identify and remedy the problem at each troubleshooting station and then as a class discussed their insights and ideas.

Teacher modeling of troubleshooting Teachers can show students how to employ diagnostic troubleshooting strategies by modeling for students how they analyze poorly functioning devices themselves. An instance of such coaching can be found in the *Design in the Classroom* Web site (GTRC, 2004b) when a student appeared not to be attending to notable performance flaws when testing a model parachute. The technology education teacher in the video, after noticing that the student was not watching the parachute's descent carefully, modeled how to make more pointed observations:

> "Watch it as it falls, from the beginning to the end."
>
> (Student releases her parachute; it partially collapses midway during descent.)
>
> "See where it stops floating slowly, and then changes speed. So you want to figure out why it's doing that."

Teacher comments and questions can help shift a student's analytical perspective and way of looking so that it includes broadening or zooming out attention in order to assess overall product performance when needed, and narrowly focusing or zooming in attention in order to conduct detailed critiques of specific subsystems and explore their connections to other parts of a device.

Matrix Pattern H. Haphazard or Linear vs. Managed and Iterative Designing

THE STRATEGY OF REVISING AND ITERATING Beginning designers *design in haphazard ways, working at random on whatever problems emerge, or they treat design as a set of strategies to be done once in linear order.* Informed designers *do design as an iterative process, while improving ideas and prototypes based on feedback and cycling back to upgrade their understanding of the problem. They manage their time and resources strategically and use design strategies multiple times in any order, as needed, in a systematic way.*

Some beginning designers move haphazardly from one emerging problem to the next, acting on impulse and in ways that seem unplanned and random. When asked at any point in their designing what strategies they might use next, they are able to identify few if any procedures to further their work. Beginning designers also follow steps to produce a finished product "as though designing is a serial/linear process," where iteration "is not in their process model" (Newstetter & McCracken, 2001, p. 68) or is described by them as a poor use of time (Adams & Fralick, 2010). The mistaken idea of design as a linear process can be conveyed through the graphics of design models employed by authors and school textbooks (Figure 4).

Informed designers agree with statements about how "Design *is* iteration" and disagree with statements about how "Good designers get it right the first time" (Mosborg et al., 2005). They are aware of the ambiguities inherent in complex engineering

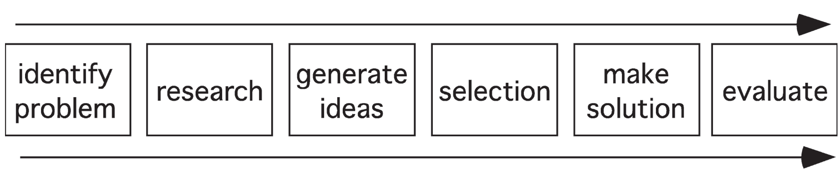


FIGURE 4. An example of a published design model that depicts engineering design as a linear process. Cited by Kimbell (1994, p. 334).

design tasks: that neither the problem nor the goals are well defined and that there are many ways to frame a problem, multiple plausible solutions, and no stopping rules other than a designer's judgment (Cross, 1992; Goel & Pirolli, 1992; Grant, 1992). In actual practice, designers cannot work in a linear fashion, since practices that often appear as a final step in design process models, such as evaluation (Kimbell, 1994) or communication (Mosborg et al., 2005), occur repeatedly throughout the process. Overall, experienced designers combine problem structuring and solving in an iterative process (Adams et al., 2003; Ennis & Gyeszly, 1991; Lawson & Dorst, 2009), self-monitor their progress, flexibly adapt to new insights (Adams, 2001), chunk strategies together to reach viable design goals (Atman et al., 2007), and strategically and opportunistically deviate from a step-by-step design process as needed (Ball & Ormerod, 1995).

Iterative design, represented in design process models as feedback loops or check-and-reflect points within and across subtasks, is considered an "integral feature" and "natural attribute of design competency" (Adams et al., 2003). It has been described as involving multiple analysis-evaluation-synthesis cycles where an understanding of the task simultaneously coevolves with developing a solution (Archer, 1979; Lawson & Dorst, 2009) as "cycles of proposal, testing, and modification of an evolving design" (Smith & Tjandra, 1998), global and local iterative cycles (Jin & Chusilp, 2005) and goal-directed transition behaviors (Adams & Atman, 2000). From our own experiences, we refer to iterations as "another pass," "the next version," or even "starting over." For it to work well, iteration in design must engage meaningful learning, where improved solutions grow out of an evolving understanding of the problem, and new insights and information get continually assimilated into a designer's understanding of the design task (Adams, 2001; Adams et al., 2003; Schön, 1983; Ullman, Herling, & Sinton, 1996; see also Patterns A and I).

Iterations may occur spontaneously, such as reacting to a particular dilemma or opportunity, strategically, such as planning to revisit and review prior design decisions about the problem, or as part of an overall design approach. The outcomes of iterative designing can be modifications to a problem, solution, or design plan, or simultaneous coupled iterations (Adams, 2001). For each adjustment made, the designer must not only analyze the effects of the change but also reevaluate the design task. Iterative problem scoping cycles (see Pattern A) result in reformulating problem requirements and modifying and adapting to changing perceptions of the design problem or constraint migration (Chandresekaran, 1992), which has been associated with the development of more creative solutions (Akin, 1994; Akin & Lin, 1995). Solution revision cycles (see also Patterns C, E, F, G, and H) may occur because a solution failed to work or satisfy one or more design requirement, or new requirements emerged during the evaluation of a solution (Braha & Maimon, 1997; McGinnis & Ullman, 1992).

The use of iteration strategies constitutes effective design practice (Adams et al., 2003) and supports learning by allowing the designer to continually revisit and reflect upon each aspect of the design task (Braha & Maimon, 1997; Bryson, Bereiter, Scardamalia, & Joram, 1991). Doing iterative designing has been found to play a significant role in the quality of final design solutions and involves "incrementally and simultaneously advancing upon both a representation of the problem and a final solution" (Adams et al., 2003, p. 286). In a comparative study where engineering freshmen, seniors, and practicing professionals were asked to do the conceptual design of a playground, increased time spent iterating (Adams et al., 2003; Adams, 2001) was associated with higher quality design solutions to a statistically significant degree.

Design iterations mark a journey from an under-specified starting point to an elusive target goal (Goel, 1989; Hybs & Gero, 1992). At any point along this journey, as designers attempt to make sense of information about the problem, generate plausible solutions, and evaluate the feasibility and desirability of solutions, they uncover new complexities or opportunities and gain new insight that may uncover hidden assumptions, missing information, or contradictions that need to be resolved. Teachers who have their students perform a design model's steps only once, who fail to explain why those strategies are relevant, or who neglect to emphasize that they might be altered or done in a different order, can leave students thinking that design steps are recipes or mere rituals (McCormick et al., 1994, p. 38) and believing that designing is a single-pass, linear process (as in Figure 4). The following teaching techniques aim to help students develop as informed designers who use iteration strategies that support continual learning while revisiting and reflecting upon each aspect of the design task (Adams et al., 2003).

Teaching strategies Understanding the role that the build-troubleshoot-improve cycle plays in iterative design and gaining proficiency in planning and managing project time are fundamental and achievable practices that students can learn. A critical and perhaps threshold concept is developing an awareness of and tolerance for ambiguity in design (Adams et al., 2003; Cross, 2001; Daly, Adams, & Bodner, 2012), as well as associated strategies for reducing or preserving ambiguity (Lande & Leifer, 2010). The following are ways for teachers to support students in becoming proficient in doing well-managed and iterative designing.

Design storyboards Teachers can collect evidence of students' haphazard or systematic designing by having them create a *design storyboard,* a graphic that holds a series of sketches or digital snapshots, from early designs to interim prototypes to final product. Such displays can be accompanied by short verbal descriptions and explanations of design decisions and aim to "document the story of how a challenge was met over time . . . each frame displaying the latest solution to the challenge" (Sadler et al., 2000).

Project and time management Teachers can help students become skillful at doing design-based project management by setting deadlines for them that "provide staging posts which focus attention on the decisions that need to be made" (Barlex & Wright, 1998, p.163). These staging posts can include establishing deadlines for sketches, requesting weekly progress reports, conducting class reviews of prototypes, and, perhaps most importantly, giving final project presentations to classmates or invited professionals who can act as outside judges (GTRC, 2004c). Since design has no inherent stopping rules (Goel & Pirroli, 1992), designers can perform too many revisions or be ineffective while doing iterative designing (Adams, 2002), as seen when overly motivated beginning designers endlessly tweak their design plans and prototypes. Such designers can benefit from being coached in "freezing a design," where a time is set after which changes to the design cannot be made. Flexibly adapting the strategies found in a design process model to meet the needs of the moment should be encouraged, but not expected of all students since it is a hallmark of design expertise. The Layers of Necessity Model (Wedman & Tessmer, 1991) articulates how instructional designers adjust their use of the ADDIE instructional design model (Smith & Ragan, 2005) based on the time remaining before a project deadline is reached.

Instruction and scaffolding for systematic design Atman and Bursic (1996) found that simply having undergraduate engineers read a textbook's description of the design process favorably impacted the quality of students' design work and resulted in them doing more transitions and using more design strategies. Case studies can depict experts modeling a variety of strategies in design thinking in various contexts (Barlex & Wright, 1998), which can help students realize the power and utility of iterative design. Teachers themselves can illustrate the role that iteration plays in design or any other design strategy through direct instruction, offering comments on student projects, or modeling such behavior using a flawed prototype or product. In one freshman year engineering course at Purdue where iterative designing was consistently scaffolded across multiple design tasks, there was a significant pre- and post-difference in the increase in importance that students attributed to the role iteration plays among a set of 23 design strategies and activities (Adams & Fralick, 2010).

Risk-taking and iteration Some students can be overly cautious when designing and need support in taking risks with their design ideas. In a meta-analysis of studies that examined the risk-taking tendencies of males and females in a variety of contexts, large gender differences were noted when intellectual risk-taking was involved (Byrnes, Miller, & Schafer, 1999, p. 378). Kimbell describes research that showed notable differences in the design work of male and female U.K. design and technology students, with girls outperforming boys in reflective tasks like investigating and evaluating ideas while boys were better at idea generation and development (Kimbell & Stables, 2008). Kimbell also noted that girls seemed to take fewer risks with their plans and ideas than boys (GTRC, 2004d). Design instructors have encouraged risk-taking by offering students case studies and personal anecdotes where accepting and building upon failure proved a viable pathway for improving design ideas. A well-publicized motto of the product design firm IDEO builds upon this idea: "Fail often in order to succeed sooner" (Kelley, 2001, p. 232).

Matrix Pattern I. Tacit vs. Reflective Design Thinking

THE STRATEGY OF REFLECTING ON PROCESS Beginning designers *do tacit designing when they think and act with little self-reflection and do little monitoring of their own or others' actions.* Informed designers *practice reflective thinking by keeping tabs on their own and others' design work in a metacognitive way and reviewing their processes and products once they have completed their work.*

Beginners do design tacitly when they act with little or no awareness of what they are doing, do not articulate what knowledge they know or need to know to further their investigations, and pay scant attention to the progress they make, obstacles they encounter, or design values that influence their decisions. They can fail to review steps they have taken or to examine the assumptions underlying their framing of the design problem. They leave their knowledge of their designs and design process implicit and unarticulated, which can limit their ability to transfer knowledge they have accumulated to new situations.

Metacognition is the knowledge and monitoring of oneself and others, tasks done, and strategies and understandings used (Flavell, 1979). For students, it involves the "ability to stands outside themselves and look in at their own designing" (Kimbell & Perry, 2001), follow their own and others' actions in order to coordinate the switching of strategies (Sternberg, 1997), and revisit assumptions when faced with evidence that their assumptions have become problematic (Perkins, 1995, pp. 218–220). At its core, metacognition in design involves a kind of reflection in action and self-monitoring that provides feedback to improve both process and product. It entails the epistemic belief that understandings change with experience (Flavell, 1979, p. 907) but can be as difficult to learn as core science and engineering concepts and design thinking itself (Flowers et al., 1986, p. 21).

Metacognitive thought is closely linked to design decision making (Kimbell & Perry, 2001) and is associated with higher levels of design performance and product quality (Adams & Atman, 2000). Informed designers reflect on the viability of the plans they propose and the lessons learned from past design efforts – both of which are manifestations of their own mental models of the system they are developing (Elmer, 2002). These ideas are common themes in studies of how designers engage in reflective practice and learn through design (Adams et al., 2003; Dorst & Lawson, 2009; Schön, 1984; Valkenburg, 1998).

Teaching strategies Early research of children designers' computer programming in Logo reported improvements in students' reflectivity and metacognitive thinking (Clement & Gullo, 1984), although such gains were limited to the contexts in which students had originally worked (Pea & Kurland, 1984). Middle school students who used Georgia Tech's *Learning by Design*™ curriculum were found to perform metacognitive thinking better than students in control classes who did no designing (Kolodner et al., 2003). The following are some of the approaches that have been created to support students' design-based reflective thinking.

Design diaries and portfolios Design portfolios can play a variety of roles in scaffolding students in their design work, even though some students maintain that they find keeping design diaries, journals, and portfolios distasteful, and do so only to enable their instructors to assess their work (Welch & Barlex, 2004). The paper-and-pencil Design Diary in the *Learning by Design*™ curriculum provided students with single-page worksheets that supported them in reflecting on what they knew and needed to learn while generating questions in the Problem Understanding sheet (see Pattern A), reviewing what they learned from early investigations in the Messing About section (see Pattern D), and combing through results of fair-test experiments (see Pattern F) in the Design Tests pages (Kolodner et al., 2004). Some portfolio systems act as a sketchbook to support creative idea production and reflection, or as a job bag to aid students in scheduling and monitoring the progress of design work; others help students showcase their ideas for final presentations (Welch, Barlex, & Taylor, 2005). Portfolios can also help students recall and evaluate key events in their individual and group design work, construct explanations for design decisions they have made, and articulate their values in engineering practice (Dunsmore, Turns, & Yellin, 2011, p. 338). Keeping portfolios can help learners describe details of their own process (Sobek & Jain, 2007), construct and articulate their own philosophy of design (Hirsch & McKenna, 2008), and make evidence-based claims about how they are prepared for future practice (Turns et al., 2010).

Compare and contrast design cases Numerous groups have engaged students in reviewing transcripts, videos, or samples of their own or others' design work to support reflective thinking in design. Students have done design tasks reported in published research, compared and contrasted their design practices with those used in the reported studies, and then reflected upon and discussed differences and similarities (Turns et al., 2003). Students can achieve highly insightful observations and reflections on what strategies and behaviors contribute to design success and failure by reviewing videos showing other design teams at work (e.g., video segments from the PBS show *Design Squad*; Purzer, 2010) or watching clips of another team doing the same design task that the students have just completed (see GTRC, 2004e). Students' understanding of design has improved after coding verbal protocols of individuals designing a playground for various design behaviors, and then later engaging in inter-rater reliability discussions (Scott et al., 2001) and critiquing protocol-analysis derived timelines that depict individual designers' processes (Atman, Deibel, & Borgford-Parnell, 2009). These approaches can lead to rich discussions regarding problem framing and formulation, differences in values that drive design decisions, and successes and challenges in doing collaborative and cooperative work in teams.

Computer-supported structured reflections Computer technologies provide a number of scaffolds that can enhance an individual's or group's reflective thinking about designing. These include (a) electronic versions of structured diaries that offer process prompts and pose structured questions to help students attend to particular aspects of their design work (e.g., Turns et al., 1997); (b) synchronous and asynchronous online systems that support learning communities in engaging in reflective social discourse (Lin, Hmelo, Kinzer, & Secules, 1999); (c) integrated assessment and learning systems that elicit student reflection in the context of design experiences, while supporting formative and summative assessment of professional design skills (Davis et al., 2011); and (d) multiple-perspective process displays that visually depict processes used from different viewpoints (Schauble, Raghavan, & Glaser, 1993).

Providing students practice in identifying their own design strategies may enhance their design-oriented metacognitive thinking. An NSF-funded *Design Compass* software has been used to support students, grades 8–16, in coding their own or others' actions while designing (Crismond, Hayes, & Danahy, 2010). The *Design Compass* scaffolds users in doing three basic functions: logging what design strategies they are using and when; archiving digital snapshots of drawings and movies of prototype tests; and viewing a histogram the compass generates that displays the aggregate times spent using various strategies during one or more design sessions. The *Design Compass* enables students to conduct more data-driven conversations about their design work with their design instructors. Such data can help students reflect on the effectiveness of their design strategy use and answer the question, "How might we have allocated our project time differently among these design strategies to improve our product and process?"

Discussion of Contributions

The Informed Design Teaching and Learning Matrix is the product of a scholarship of integration for engineering education that links a broad-based and multidisciplinary scholarship of design cognition with an emerging scholarship of teaching and learning in engineering design. Some of the challenges faced by this scholarship of integration effort include (1) simplifying the scale and complexity of the cross-disciplinary design research landscape, (2) formulating learning goals and gathering design strategies that have been used to help designers learn to design, and (3) fashioning a use-inspired tool to enable teachers to develop their own Design PCK and help students become informed designers. Below, we summarize the key points related to the theoretical and practical contributions of this effort and note limitations that open up opportunities for further research and development.

We see two major audiences for this paper and its scholarship of integration approach. For researchers, the Matrix contributes to educational theory the notion of informed design and key performance dimensions that students may achieve during their formal education in K–16 settings. The Matrix also acts as a framework for enabling researchers to (a) situate existing research findings related to engineering design cognition and studies of the impact of various instructional methods on student design learning; (b) identify gaps in the field's current research base; and (c) connect and situate results from future engineering education research as well as validate and improve the current Matrix and educational theory of informed design.

For teachers, the Matrix may be helpful in building their own Design PCK and improving their classroom practice when using engineering design activities. The Matrix helps do this by directing teachers' attention to common design misconceptions and habits of mind of beginning designers, suggesting performances that students might achieve as informed designers, and then compiling for teachers learning goals linked to instructional strategies that are relevant to the patterns noted in the Matrix.

Implications for Educational Theory Building and Research

Bruner (1964) and Reighluth (1999) distinguish between two kinds of educational theories: ones that are mainly descriptive and deal with learning and development, and others that are more prescriptive and offer guidelines on what ideas and skills should be taught (i.e., learning goals) and suggest ways to achieve those goals effectively and efficiently (i.e., teaching strategies and pedagogy). In the following paragraphs, we describe how the Matrix acts as an emergent educational theory and offer suggestions for improving engineering education.

The Matrix rests upon the notion of informed design and its collection of key performance dimensions. When placed into service as a research framework, the Matrix can situate existing studies, as illustrated in the Unpacking section of this paper, while pointing to gaps in the current research literature. For instance, studies regarding problem framing have been done in elementary grades (Roth, 1995) and undergraduate settings, but not middle school or high school venues. The Matrix as a research framework can also reveal opportunities to study the relationships between predictor variables related to design behavior (single or combined patterns) and measureable outcomes of students' design work (e.g., performance of final products) and thinking (e.g., explanations for design decisions). It can then provide a theory-based structure onto which new studies may be hung.

Although the Matrix's starting points and end points may need further refinement through empirical validation studies, and additional research will more finely differentiate the Matrix's current two-step progression statements, it still represents a crucial first step towards developing a comprehensive conjectural model of K–16 design learning progressions (NRC, 2007). Such work would require developing suites of psychometric instruments that can reliably measure students' use of design strategies over large tracks of time and across different instructional contexts. Longitudinal studies that follow students' learning of engineering design could reveal, hone, and refine detailed learning progression statements that would make "informed teaching" with design activities more possible for all.

The Matrix may also be combined with other theoretical frameworks to give rise to new research questions, including "How is development of informed designer practices related to students' educational experience, motivation, self-efficacy, or persistence in STEM fields?" Basic research could validate or refute causal claims linking aspects of design practice with the quality of students' design products, thinking, and learning. Developmental studies could identify critical thresholds and investigate the applicability of design patterns across a wide age range from childhood to early adulthood.

This emergent instructional theory of informed design provides guidelines on ways to improve students' design learning. Here, the emphasis shifts from explaining students' design capabilities to offering a palette of viable learning goals and effective teaching strategies, from which formative and summative assessments can be devised. This theory may stimulate new research questions on pedagogical and teacher professional development issues, such as "Which teaching practices best support specific elements of design learning?" "What workshop and other experiences support teachers in developing their own in-depth Design PCK?"

Implications for Practice: Using the Matrix in the Classroom

Efforts at improving teaching practice are often disconnected from educational research and theories (Sowder, 2000; Arbaugh et al., 2010). The Matrix attempts to bridge this gap by referencing and compiling research studies into a theory-based framework for researchers and a planning tool and observation guide for teachers. Central to the Matrix's practical contributions is its aim to help teachers see their students' design work from the perspectives of an experienced design researcher, design educator, and a cognitive and learning science researcher. In the following paragraphs, we provide three examples of practical applications from professional development workshops for teachers and from high school and college contexts for students. These illustrate how the Matrix can (1) provide teachers with a first-generation representation of Design PCK to help them construct an evolving set of Design PCK understandings and schemas; (2) help teachers and students monitor students' evolving design skills, concepts, and dispositions; (3) broaden the range of strategies that teachers use when using short- or long-term design projects; and (4) improve students' understanding of engineering design and ability to assess their own design practices and work.

Teachers in professional development workshops and graduate courses The Matrix has been used to build teachers' awareness of Design PCK in recent professional development workshops involving in-service elementary teachers, middle school technology education and high school engineering teachers (e.g., Crismond & Peterie, 2011). At these venues, teachers learned about design misconceptions and differences between beginning and informed designers, compared and contrasted the practices of scientific inquiry and engineering design, and aligned new national science standards (NAS, 2012) to the Matrix' learning goals and instructional approaches.

A series of three graduate education STEM methods courses were taught at City College of New York from 2011 to 2012 (Crismond & Adams, 2012), where in-service teachers from New York City in the first semester learned about hands-on materials and pedagogy related to scientific inquiry, and then in the second semester focused on doing and using engineering design tasks with children. Drafts of this Matrix paper were the main reading of the second course, where teachers for their final projects redesigned and implemented published, design-based curricular materials with their students. The final course in the series, Teacher as Designer, had teachers apply what they learned about engineering design to solving instructional and other school-based problems they typically face in their work (e.g., redesigning space in a classroom or the school building, designing layouts of pages or handouts for students, developing alternative summative assessments to show what students are learning). Teachers used a rubric that was based on the first three columns of the Matrix with an additional column where teachers could cite evidence to support their assessment of students' engineering design practices. The instructor also used the same rubric when rating the design practices teachers used during the course and in completing their final projects.

As an example of this work, a grades 4–5 science cluster teacher recently used the Matrix after developing initial lesson plans for an instructional unit from the NSF-funded curriculum series, *Engineering Is Elementary* (Museum of Science, 2009). This curriculum employs a five-step design process model of Ask, Imagine, Plan, Create, and Improve. The *Catching the Wind: Designing Windmills* module asks students to redesign a blade configuration for a model windmill so that the model generates the maximum torque. The teacher first developed a two-page lesson plan and then, in consultation with author Crismond, reviewed the Matrix with reference to this plan. An analysis of the recorded and transcribed collaborative session revealed the following sequence of activities: (1) the teacher explained to Crismond his lesson plan and key planning decisions; (2) Crismond gave an overview of key points from the Matrix of Informed Design; (3) both aligned the five strategies from the EiE curriculum's design process model to those in the Matrix (e.g., Ask mapped to Patterns A and B, Imagine mapped to Pattern C, etc.); (4) the teacher identified objectives from the Matrix's learning goals column to include in a revised lesson plan (e.g., a revised emphasis on using design as a context for doing controlled experiments (Pattern F) and troubleshooting (Pattern G)); and (5) the teacher selected techniques from the Matrix's teaching strategies column that he felt met his students' learning needs. For a final project, the teacher implemented the lessons and collected formative assessment data that focused on students' troubleshooting thinking and that helped him to make adjustments to daily instruction.

High school students The Matrix has been used with high school engineering and physics students to do direct instruction about the differences between beginning and informed designers and to support class discussions of those behaviors (Crismond & Peterie, 2011). Students rated themselves along the beginning-informed design continuum for each of the Matrix's patterns and provided evidence for those ratings based on their recall of recently completed design project work (Figure 5). These activities not only provided formative assessment data that helped the instructor better understand students' grasp of specific design strategies and their concepts of informed designing, but also afforded students with an opportunity to "self-evaluate and reflect" (McTighe & Wiggins, 2004, p. 214) upon their own growth towards becoming informed designers.

College students In a first-year undergraduate engineering course, author Adams used the Matrix to scaffold design learning as her students worked in teams on increasingly complex and large-scale design tasks. She presented the Matrix and repeatedly referred to its language and ideas to help students understand how design is different from closed-ended engineering problem solving and self-assess their own growth as informed designers. Students also used the Matrix to help them critique and predict the strengths and weaknesses of other design teams seen in video segments from the PBS program *Design Squad* (see also Purzer, 2010). In class, students discussed their observations of what they saw as effective and ineffective design strategy use and mapped these to the Matrix's descriptions of beginning and informed designing.

Another study, also conducted in a first-year engineering program, suggests that the Matrix has promise as a tool for direct instruction and student self-assessment. A pre- and post-test survey was administered to 115 engineering freshmen, who were asked to rank from a list of 23 design activities what they felt were the *most* and *least* critical activities for producing high-quality designs (Adams & Fralick, 2010). By semester's end, there was a significant shift in awareness of the ambiguity inherent in design tasks and the need for adopting an iterative approach to design (Pattern H). In the pre-activity survey, students

Matrix Pattern	Students' Recalled Examples of Their Own Behavior as… …Beginning Designer	…Informed Designer
A. Solve Problems Too Soon vs. Wait to Learn More	In our project, only one step was done before testing, which was building. We could have looked thru the problems and verify what we needed to do.	[Our teacher] told us information about parachutes and I did not make a design until I understood everything I could about a parachute.
…	…	…
H. Single Design Cycle vs. Iterative Designing	For the paper car activity, as a class, no one did any redesign in their project to make it better besides small tweaks to the same design.	On our parachute design, we had to go through the design process cycle about four times before getting our final projects.

FIGURE 5. Modified Matrix table filled with students' own examples of acting as beginning or informed designers. In this table, the language associated with each Matrix pattern (column 1) was modified to make it more accessible to students.

were more likely to identify iteration as one of the least important design activities for producing solutions of high quality, citing iteration as an "inefficient use of time," a "waste of time," and how good teams "shouldn't have to iterate much." Students' post-activity responses in effect moved iteration from the least important to one of the most important design activities. Students wrote of how iteration "continuously makes the design better" and is an "extremely useful process that allows you to re-look at different aspects of your design and decide what to improve on." One student explained how "having a plan is important, perhaps vital, but so is being flexible with the plan and being able to adapt to the current circumstances of the project." There were also significant shifts in students' recognition of the centrality of problem formulation strategies (Patterns A, B, and H) such as understanding the problem, gathering information, and identifying constraints (e.g., "an insufficient problem statement can derail a project and can cause delays later in the project").

LIMITATIONS OF THE MATRIX

While this scholarship of integration effort is provocative in articulating a new language for design learning and teaching and is powerful in providing direction to the next phase of crucial work, it has its limitations. First, while developing the Matrix, the authors made difficult decisions regarding the scope of the scholarship of integration effort. To manage complexity and feasibility, we have left a number of substantial challenges for future work. One involves reviewing and integrating what might be included in an informed designer's understanding of the nature of engineering design (Lewis & Zuga, 2005, p. 55). This understanding has analogues to the concept in science education of the nature of science (Lederman et al., 2002) and in engineering education of the nature of engineering (e.g., Karatas et al., 2011). The social aspects of design (Bucciarelli, 1996, 2002), including the challenges of helping students develop their abilities to collaborate and cooperate in design teams and learn through their interactions with their peers, also have not been articulated in this version of the framework. The role of communication and social interactions in designing – whether it is within or across teams, disciplines, cultures, or broader stakeholder audiences – is not addressed. In addition, more idiosyncratic, though critical, issues related to learning to use tools, work with various materials, and fabricate prototypes – tasks that typically do have a place in undergraduate cornerstone engineering courses (e.g., West, Flowers, & Gilmore, 1990) – have not been included in this version of the Matrix.

The scope of the Matrix has, by design, been constrained to K–16 instructional settings. Its primary audiences include K–12 STEM educators, engineering educators at the undergraduate level, and potential early career professionals or graduate students. However, much of the research represented in this paper does not address the special concerns or learning issues of K–2 students. This limitation represents not only a gap in the field of engineering education but also a significant opportunity since, for example, it is quite unclear whether these younger students can frame design problems effectively or use abstractions found in systems thinking to understand how everyday products work. Since the Matrix spans childhood education to early adult education, future studies would need to target issues that bridge different learners in different contexts. Also, it is quite possible that some K–16 students have considerable design experience and have engaged in deep reflection such that their learning trajectories may extend beyond that of informed designing. While this does not suggest that the information contained in the Matrix is incorrect, it does highlight the need for research to support adjusting Matrix end points closer to expertise. Finally, the Matrix was designed to help teachers reflect on and develop their own Design PCK but does not represent or fully articulate what makes up any teacher's Design PCK. Such an endeavor would require dedicated studies on what K–16 teachers understand about design knowing and learning, and this shapes their instructional approaches using design tasks.

Conclusions

The outcomes of this scholarship of integration process include the articulation of the idea of *informed design* upon which the Matrix is based. The Matrix table acts as a guide to help teachers identify, diagnose, and explain some of the highly ineffective design habits of students. It also aims to help teachers formulate pragmatic learning goals and compile a suite of teaching activities and techniques to use or adapt as needed. Critically, the Matrix is the place from which teachers can formulate their own formative assessment tasks, and it can help them implement evidence-based adjustments to their day-to-day instruction. The Matrix aims to be a first-generation construct of the Design PCK that teachers need to know and develop to be effective users of design tasks with their students.

With these complementary tools in hand, an emergent instructional theory for teaching informed design was proposed, and the use of the Matrix as a conceptual *framework* for placing and locating disparate and separate research findings was also suggested. The Matrix may also serve as a place where new findings from studies on the effectiveness of the teaching remedies and the results from longitudinal studies that follow students' learning of engineering design over large tracks of time can be integrated. Also, descriptions of beginning designers and the steps they follow towards becoming informed designers could be revised, refuted, or validated. Such data could lead to the honing and refining of a series of detailed learning progressions statements for engineering design that will make effective teaching with design activities a more achievable goal for teachers.

Helping support *informed teaching* with engineering design activities is an ultimate goal of this work. This would include helping teachers to (a) look for and notice inefficient behaviors and habits of mind of beginning designers, (b) select realistic learning objectives that aim to improve particular design behaviors or address one or more of the seven performance dimensions of informed design, (c) create viable formative assessments tasks to assess students' growth in engineering design practice, and (d) coach students in using the Matrix themselves to guide their design actions and support meaningful reflective practice. Such practices can represent a significant shift from seeing instruction in engineering design as teaching projects to creating design-based learning experiences that provide students with opportunities to engage in "approximations of practice" (Grossman et al., 2009) and even experiment with provisional identities as future designers and engineers.

How a Matrix Learns

The Informed Design Teaching and Learning Matrix, as with any building (see Brand, 1994), can learn and adapt through feedback. Comments and questions regarding this paper and its contents may be sent to David Crismond, City College of New York, 138th St. & Convent Ave., NAC Building 6/207b, New York, NY 10031, or emailed to dcrismond@ccny.cuny.edu. Feedback might include (1) *applications*, how have you used the Matrix in your classrooms or in teacher professional development settings; (2) *feedback*, what worked well and poorly when you read or used the Matrix; (3) *gaps*, what seems to be missing in the Matrix's current collection of patterns and misconceptions and formulations of starting points and endpoints; and (4) *teaching techniques*, what goals and strategies of instruction reported in the literature might be included in the Matrix.

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