

2016

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Shannon Chance

Technological University Dublin, shannon.chance@tudublin.ie

John Marshall

The University Of Michigan, johnjm@umich.edu

Gavin Duffy

Technological University Dublin, gavin.duffy@tudublin.ie

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Recommended Citation

Chance, S., Marshall, J. and Duffy, G. (2016) Using Architecture Design Studio Pedagogies to Enhance Engineering Education. *International Journal of Engineering Education* Vol. 32, No. 1(B), pp. 364–383, 2016. doi:10.21427/D7V62S

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Using Architecture Design Studio Pedagogies to Enhance Engineering Education*

SHANNON M. CHANCE

Dublin Institute of Technology, College of Engineering and the Built Environment, Bolton Street, Dublin 1, Ireland.
E-mail: shannon.chance@dit.ie

JOHN MARSHALL

University of Michigan, Penny W. Stamps School of Art and Design, Ann Arbor, Michigan, 48109, USA.
E-mail: johnjm@umich.edu

GAVIN DUFFY

Dublin Institute of Technology, School of Electrical and Electronic Engineering, Kevin Street, Dublin 2, Ireland.
E-mail: gavin.duffy@dit.ie

Problem-Based Learning pedagogies that require high levels of inquiry and hands-on engagement can enhance student learning in engineering. Such pedagogies lie at the core of studio-based design education, having been used to teach architects since the Renaissance. Today, design assignments and studio-based learning formats are finding their way into engineering programs, often as part of larger movements to implement Student-Centered, Problem-Based Learning (PBL) pedagogies. This spectrum of pedagogies is mutually supportive, as illustrated in the University of Michigan's SmartSurfaces course where students majoring in engineering, art and design, and architecture collaborate on wickedly complex and ill-defined design problems. In SmartSurfaces and other similar PBL environments, students encounter complex, trans-disciplinary, open-ended design prompts that have timely social relevance.

Analyzing data generated in studio-based PBL courses like SmartSurfaces can help educators evaluate and track students' intellectual growth. This paper presents a rubric for measuring students' development of increasingly refined epistemological understanding (regarding knowledge and how it is created, accessed, and used). The paper illustrates use of the tool in evaluating blogs created by students in SmartSurfaces, which in turn provides evidence to help validate the rubric and suggest avenues for future refinement. The overall result of the exploratory study reported here is to provide evidence of positive change among students who learn in PBL environments and to provide educators with a preliminary tool for assessing design-related epistemological development. Findings of this study indicate design-based education can have powerful effects and collaborating across disciplines can help engineering students advance in valuable ways.

Keywords: problem-based learning; student-centered learning; design-based learning; epistemology; architecture education; design studio pedagogy; engineering education; cognitive development

1. Introduction

Problem-Based Learning pedagogies that require high levels of inquiry and hands-on engagement provide a way to enhance students' learning and development in engineering. These pedagogies are at the core of studio-based design education and have been used to teach architects since the 1500s, when architecture gained recognition as a distinct profession in the Western world. Successful integration of Problem- and Project-Based Learning (PBL) pedagogies into architectural education has helped ensure consistent supply of creative, flexible problem-solvers who can negotiate disparate concerns, and think across scales [1].

In the US, the National Science Board sets directives for the National Science Foundation and has mandated "*Engineering education must change in light of changing workforce and demographic needs*" [2, p. 1]. The Board strongly recommends use of PBL and other Student-Centered

Learning (SCL) pedagogies. Despite vehement and ongoing requests, however, strikingly little has changed in the average engineering classroom—within the US or around the world [3].

Exposing engineers to the design studio pedagogies used in architecture—as has occurred in the University of Michigan's SmartSurfaces course—can help raise familiarity and comfort with both the format and its teaching methods [4, 5]. It can also improve student learning, is evident among students in SmartSurfaces who have created blogs [6]. A number of these blogs provide evidence of cognitive, intellectual, and epistemological growth as defined by social psychologists and scholars of 'student development theory' [7–10]. In this studio, students worked in groups of six—typically with two engineers, two architects, and two art and design majors per group.

In this paper, we argue for more extensive use of context-dependent, open-ended, project-based approaches in the education of engineers. More

specifically, we believe that engineering educators can enhance student learning by: borrowing successful pedagogies from architecture, learning from previous instances of collaboration among engineers and architects (such as the SmartSurfaces course), and incorporating theories about cognitive and epistemological development. We show how to do this, provide a rubric for evaluating student development, and describe results of an exploratory study using this rubric to identify instances of student growth.

Key findings reported in this paper are that (1) architecture design studio helps students practice higher order thinking and provides a format that educators should consider integrating into engineering in ways similar to SmartSurfaces and (2) our rubric provides a reasonable tool for helping identify outcomes with respect to learning new design strategies and, to a lesser degree, learning new epistemological conceptualizations.

2. Literature review

Student-Centered Learning pedagogies used in engineering education include PBL, enquiry learning, discovery learning, case-based teaching, and just-in-time teaching. A unifying theme of these approaches is that they are inductive. In them, the problem or project is presented first and this drives the learning so that students develop questions before seeking answers. SCL pedagogies focus attention on the learner's needs and abilities. They aim to help students achieve higher levels of engagement and thinking than required in more traditional formats where the teacher and the teacher's knowledge take center stage [11, 12].

SCL methods have been found to encourage deep learning and improve critical thinking and self-directed learning; they are based on theories of learning and scientific understandings of how the brain functions [13]. An empirical study conducted in 2011 found that learning gains among 55 electrical engineering students in PBL were double the gains of students in traditional, control-group lecture courses [14]. These encouraging findings suggest the need for additional research to identify and assess specific types of learning outcomes that result from SCL.

Following a discussion of collaborative, multi-disciplinary, design studio formats, we describe an example that uses such pedagogies. This example—the University of Michigan's SmartSurfaces course—is used for analysis later in the paper. The literature review culminates by discussing cognitive and epistemological development, explaining the assessment rubric, and describing how it was developed.

2.1 Collaborative, multi-disciplinary, design studio formats

Design studio courses that are both collaborative and multi-disciplinary are emerging on campuses across the USA. Examples can be found in dozens of universities that have competed in the United States Solar Decathlon. They are also evident in the multi-week competition studios held annually at the University of Oklahoma's College of Architecture and in the University of Michigan's SmartSurfaces course, just to name a couple. Combining all four of these techniques, in a coordinated and refined way, still proves to be challenging and rare. In the passages below, we discuss each aspect separately and identify where it is most often found.

2.1.1 Design assignments

Design projects help put engineering and science concepts in context to help make them less abstract. In contrast, assignments in labs and lecture courses frequently lack the context necessary to make them meaningful to students [15]. By engaging in design projects, students not only see relationships in the broader context, but they also learn to identify various aspects of 'the problem' in tandem with 'the solution' [16]. They learn to analyze, evaluate, and synthesize information, as well as conduct experiments, think iteratively, direct their own learning, and adapt more readily to the changing context and requirements of professional practice [1, 17]. The National Science Board asserts that such pedagogical techniques make engineering more relevant to a broader group of students and help attract and retain more diverse individuals [2].

Many other sources are available to assist in this realm. For instance, the book *Design Knowing and Learning: Cognition in Design Education* provides tools engineering educators can use to integrate design thinking into engineering education [18]. The journal *Design Studies* also provides useful examples. One easy way of learning to integrate design into engineering courses is to collaborate on projects with architects and architectural educators, as exemplified in the SmartSurfaces example below.

2.1.2 Studio formats

The design studio format involves high levels of SCL. Here again, learning is inductive, problem-driven, and realized through project work. The terms 'design studio' and 'atelier' and are commonly used to describe (1) an artist's workshop, (2) a place where architecture, art, and design are practiced or learned, or (3) locations where skilled workers produce finely crafted objects. The studio is often conceptualized as an experimental design laboratory or workshop. In addition to being used world-

wide to teach architecture, this approach is sometimes also employed in the education of urban planners, engineers, and scientists [19, 20]. Schools of medicine and art are known to use similar techniques as well [21].

Our review focuses on the way studios are used in learning and teaching architecture, because of the technical similarities between architecture and engineering. Although the design studio itself has not been used as extensively in any engineering program as it is used in architecture, it is a standard feature of many engineering firms. Arens, Hanus, and Saliklis have argued that the studio-based model “is particularly well-suited for the education of engineers because of its attempt to blend both art and science in the ‘learn-by-doing’ experience” [17, p. 5].

In architectural education, students spend a majority of their time in design studio courses that are supported by a variety of more traditional, lecture- or seminar-format courses where specific technical, theoretical, or historical content is delivered. The students actively engage with and apply content while completing design assignments in their studio courses. Design projects are vehicles that help students develop concepts and apply critical thinking to an increasingly complex range of issues as they matriculate. Most architecture students complete an architecture design studio every semester while in the university, and their design studio carries far more weight (credit- and contact-hour wise) than any other course in the architecture curriculum.

It is interesting to note that accreditation for undergraduate architecture programs has historically emphasized high-order thinking skills, whereas engineering accreditation has tended to emphasize lower-order thinking skills, leaving the development of high-order thinking skills for post-graduate education [17, 22, 23]. Studio-based architecture courses consistently require analysis, evaluation, synthesis, and creation. Students must be able to verbally justify their responses. Teachers model this ability and the use of higher-order thinking skills as they evaluate and critique student work.

Some engineering educators complain that this type of delivery (i.e., context-driven, just-in-time) neglects too much content. This issue is widely acknowledged in architecture. With regard to building design, educators are prone to leave the acquisition of specific bits of knowledge (including many zoning regulations, building codes, legal and cost factors) for students to learn during their professional internships. Teachers sometimes sacrifice delivery of technical content in favor of helping students master ‘design thinking’ skills, as reflected in accreditation standards that require ability in design thinking, communication, formal ordering

systems, and the like, but require just understanding of legal and regulatory issues. One net result of studio-based education is in fostering self-directed learning, which is an aspect embedded in accreditation standards of the USA’s National Architectural Accrediting Board [22].

The organizations that define, regulate, and teach architecture in the USA commissioned a three-year study by the Carnegie Foundation for the Advancement of Teaching. The researchers—education experts Ernest Boyer and Lee Mitgang—came to the conclusion:

- “architectural education is really about fostering the learning habits needed for the discovery, integration, application, and sharing of knowledge over a lifetime.” [1, p. xvi]
- “The study of architecture is among the most demanding and stressful on campus, but properly pursued it continues to offer unparalleled ways to combine creativity, practicality, and idealism.” [1, p. 5]
- “We are convinced that architecture education, at its best, is a model that holds valuable insights and lessons for all of higher education.” In fact, we found it to be “one of the best systems of learning and professional development that has been conceived.” [1, p. 5]

2.1.3 Collaborative processes

Collaboration has been more highly prized in the professions of engineering and medicine than in architecture. Techniques for prompting and managing group-based learning were initially pioneered in medicine [21] and they have been implemented in an increasing number of engineering schools over the past two decades [24]. Although architectural accreditation in the USA now requires every student to experience collaboration across multiple disciplines, effective techniques and standards of behavior for collaborating are only now beginning to emerge in the field [25]. Fortunately, architecture educators have recently begun to integrate collaboration in ways that prepare students for group work required in the field. This section focuses on the use of group work in engineering education.

When a structured approach to collaboration is used in engineering education, students typically work in groups of four to twelve members [26]. Groups explore a problem or project that is aligned with their prior knowledge but that requires them to stretch beyond it. PBL groups are often advised to follow an iterative process of brainstorming, research and self-directed learning, and reporting. During brainstorming phases, the group discusses the problem and suggests possible paths and alternative solutions for investigating it. Group mem-

bers who are familiar with the formal methods of collaboration that underpin PBL know to query each other for current understanding. This enhances their learning and helps students build skills in communication, negotiation, and conflict resolution. As students reconvene during the design process, they review progress and report findings from research. After having addressed issues from the last meeting, the group starts the cycle again by identifying what to do next, delegating new tasks, and so on.

Few students know how to operate in this way when they first encounter problem-based group-work. They often arrive in university with vastly different experiences of education and expect content to be delivered for memorization and recall. Often, collaborative PBL does not align with their expectations of the learning process. They do not yet see knowledge as something they can create, author, or construct.

In cases where students have trouble learning with and from peers, the tutor must intervene. In the early stages of a PBL program, students need frequent, formative feedback regarding how to learn, how to guide their own learning, and what types of steps a group can follow in order to be successful [27]. Early on, the tutor seeks to ask 'directing' questions, checks understanding, ascertains if tasks have been completed, and helps summarize learning. The tutor must openly question the group's decisions, encourage equal participation, include everyone in discussion, help ensure everything is recorded, help keep the group focused, and (here again) summarize learning that has occurred [21].

Over time, students understanding of knowledge may evolve, as demonstrated in the SmartSurfaces example to follow. As students become comfortable with the idea of formulating questions and answers for themselves and demonstrate emerging ability to do so, the teacher can begin to relax the focus on process. When this happens, assessment should shift likewise—from emphasizing 'process' at the outset to emphasizing 'product' in later years. In PBL, products typically include reports, presentations, artifacts, and the like.

A primary benefit of group-based PBL in engineering has been that students concurrently develop technical and non-technical knowledge and skills. Engineers should be attracted by the optimization that such concurrent development offers. It is important for educators to acknowledge that learning to work in groups and to self-direct one's learning takes time and effort. Assessment and feedback must support students in this endeavor. The teaching strategies, learning goals, curricular content, and grading procedure need to align in order to create

an effective environment for learning. Once these skills are developed, however, students can be much more independent in managing learning, thereby requiring less input from academic staff.

In engineering, the use of group-based problem-driven pedagogies has fostered success in developing a wider range of graduate attributes. In one recent study, employers rated graduates from an institution that used such techniques much higher on a range of non-technical skills than their counterparts who encountered more traditional methods [28].

2.1.4 Multi-disciplinary focus

Multidisciplinary or interdisciplinary team skills are considered important for industry, and as such are required for programs that are certified by the Accrediting Board for Engineering and Technology (ABET) whose General Criteria '3d. Student Outcomes' stipulates "an ability to function on multi-disciplinary teams" [29]. Gibbons *et al.* have questioned the adequacy of traditional disciplinary structures within universities with regard to broader social, technological, and economic contexts, arguing for a mode of knowledge production that is context-driven, problem-focused, and interdisciplinary [30]. They argue that this newly emerging mode reflects the need to accomplish tasks at the boundaries and in the spaces between different communities.

This new mode has brought about a need for increased collaboration, integrative problem solving, and the development of new hybrid fields. The Association of American Colleges and Universities has argued that universities need to change their practices to develop students as "integrative thinkers who can see connections in seemingly disparate information and draw on a wide range of knowledge to make decisions" [31, p. 21]. The National Academies have recommended "students should seek out interdisciplinary experiences, such as courses at the interfaces of traditional disciplines" and that "schools introduce interdisciplinary learning in the undergraduate environment, rather than having it as an exclusive feature of the graduate programs" [32, p. 55].

2.2 SmartSurfaces example course

The University of Michigan financed development of a series of multi-disciplinary, team taught courses that included SmartSurfaces, which was designed and conducted by professors Marshall, Shtein, and Daubmann [4]. For a period of three years, they offered a collaborative design studio for students from materials science engineering, art and design, and architecture to work together. Of the techniques described above, multi-disciplinary, design process

and studio format were explicitly covered in the course. Although collaborative practice was required, no specific process or format was presented for students to use.

Most participants in SmartSurfaces were undergraduate students in third or fourth year. The course was elective/optional, and although it required an extraordinary level of student time and engagement, it did not take the place of any required course. To put this in context for those outside the USA: a three-credit course in this system is roughly equivalent to five ECTS credits in the European Credit Transfer and Accumulation System. American undergraduate students typically complete 12-18 credits per semester, with 120 credits required to earn a typical Bachelor's degree and a minimum of 150 credits required for a Bachelor of Architecture first professional degree. Architecture studio courses most typically carry five-six credits.

In SmartSurfaces, multi-disciplinary teams of six worked together to design surfaces that had specific 'smart' properties. The exact nature of these properties was not clearly defined by the teachers. As such, the student groups had to grapple with possible meanings—identifying problems and solutions simultaneously as they worked. As the groups navigated through a series of ill-defined problems, they learned to balance group dynamics and develop a shared sense of authorship.

In 2009, each team was required to design, build, program and test a Heliotropic SmartSurface. In 2010, each team produced a Biomimetic SmartSurface. The project was more explicitly aligned with social concerns in 2011, when each team developed a SmartSurface for 'Power House'. The Power House project was more service-oriented than prior years' projects and was developed with and for a nonprofit organization that works to develop and implement stabilization strategies for a specific neighborhood in Detroit, Michigan.

Each year, the students faced very open-ended problems to which the professors did not have predetermined answers. This is a crucial part of the context that sets this example apart from many other PBL problems that are quite safe. Kolmos discussed three categories of problems, distinguished by the extent to which they are open-ended: Assignment project, subject project and problem project [33]. A PBL module can address an 'assignment project' whose solution is known in advance to the tutor, or it can be more open-ended with students allowed some control over the problem setting or methods used to solve it. The SmartSurfaces course appears to have adopted the most open-ended type, labeled as 'problem project' by Kolmos. Here, students must first frame the project or define what the problem is before starting

to solve it because their tutors do not have solutions in advance and are, therefore, not in a position to step in and take over. The students are very much in control of the learning process.

SmartSurfaces students reflected on and recorded their experiences on using individual, publically accessible Internet blog sites. The blogs serve to describe and document learning that occurred as a result of the design assignments, studio format, collaborative practices, and multi-disciplinary nature of the course.

Prior research indicates success in SmartSurfaces. A follow-up survey conducted after the 2009 version of the course by the university's Center for Research on Learning and Teaching (CRLT) indicated high levels of student learning [34]. Students reported having developed strong skills in critical thinking, oral communication, and creative thinking. In fact, SmartSurfaces students described levels of learning that far exceeded the levels reported by students in the other eight University-funded multi-disciplinary team-taught courses.

2.3 Personal epistemology & intellectual development

This section identifies the theoretical underpinning of a rubric created for the purpose of assessing design students' epistemological development.

2.3.1 Relationship to engineering education

To gain accreditation by a given professional body, an engineering program must achieve a set of program outcomes defined by that body. A paradigm shift has occurred in the last few years to place increased emphasis on non-technical skills thereby challenging engineering programs to facilitate the development of both technical and non-technical skills during the college years. Many of the non-technical expectations require an advanced epistemology that cannot be assumed to exist among a young undergraduate cohort of students. For example, "the ability to plan and carry through self-directed continuing professional development to improve their own knowledge and competence," a requirement of Engineers Ireland [35] requires students to conceive of knowledge and learning in a way that Perry described as 'relativism' [7]. Students who view academic figures as the gatekeepers of knowledge, and expect to be told what to do in their studies, will inevitably face a highly disjunctive experience when challenged to set their own learning goals.

Facilitated appropriately and using open-ended problems, PBL requires students to confront such epistemological challenges as undergraduates rather than postponing open-ended encounters until their final-year capstone projects or post graduation. Therefore, in addition to enhancing

the learning of technical content, PBL affords personal development at the epistemological level through confronting uncertainty and at the practical level through, for example, working closely with others in a group. By seeing engineering students as individuals with epistemologies, engineering educators can work to improve and mature those epistemologies to more closely match the requirements of accrediting bodies. PBL is a method for learning and teaching that is aligned with such an aspiration.

2.3.2 Epistemological development theories

Scholars of ‘student development’ explore topics ranging from student engagement, to the development of purpose and identity, to patterns of intellectual, cognitive, and epistemological development. This particular study focuses on the last set— involving intellectual, cognitive, and epistemological development.

In 1970, Harvard professor William Perry published the first of many schemas describing the intellectual development of college students [7]. These schemas identify attitudes, perceptions, and behaviors students typically display in college as well as the order (or pattern) in which these typically unfold among American college students. Of central focus is the student’s ability to navigate complex

issues, view issues from multiple points of view, make decisions in context, and commit to a contextualized and contextually ‘relativistic’ way of thinking.

Table 1 is helpful in understanding how an individual’s conception of knowledge typically changes over time. It shows how such changes relate to Perry’s schema of intellectual development. Perry’s categories are listed across the top of Table 1, with simplistic ways of thinking on the left, moving toward more sophisticated ways of thinking on the right. The bold line on the right side of the table represents a marked turning point in the way individuals contextualize their interpretations. Perry called this transition ‘Revolutionary Restructuring’ [7]. Love and Guthrie describe this as ‘The Great Accommodation’ [10]. As noted earlier, most scholars believe it is rare for students to cross this threshold during their undergraduate years.

Experts agree that students typically enter college with reliance on a limited set of familiar strategies for learning [37] and with relatively fixed ideas about knowledge and the role of authority in determining truth and defining knowledge [7, 10]. Moreover, they have noted that many students do not develop as quickly as they should during their undergraduate years, with regard to epistemological development [10, 38]. We believe it is the role of educators to

Table 1. Typical changes in how students view knowledge [36].

	Low Level Development		→	Revolutionary Restructuring	→	High Level Development
	Dualism	Early Multiplicity		Late Multiplicity		Contextual Relativism
What is Knowledge?	Knowledge is a collection of absolute truths and there’s a right and a wrong answer to everything.	Knowledge is mostly certain and there’s a right way to find the right answers.		Knowledge is certain in only a few areas, and therefore all opinions are fairly equal.		Knowledge is context-dependent and its validity can only be judged in context, by using appropriate thinking processes.
What is the teacher’s role?	Source of knowledge.	Model of the right way to find knowledge.		Model the use of good thinking process—but may be completely discounted.		Expert guide and consultant, able to make valid decisions in context.
What is the student’s role?	Absorb information and learn the right answers.	Work hard to learn, including how to learn, processes required for tasks, and how to apply these processes.		Learn to use evidence and think independently.		Use the intellect in various contexts and apply ‘rules of adequacy’ to assess ideas, information, and decisions.
What is the peers’ role?	Peers do not have valid knowledge.	Peers have some valid knowledge, but the teacher knows the answer best.		Peers have legitimate ideas, and their opinions may not matter.		Peers who can think in context and use appropriate rules in the process of forming judgments offer valuable opinions and experiences.
What support is needed?	Desires structure.	Desires clear task instructions and evaluation guides.		Enjoys diversity and independence. Shirks structure.		Comfortable transitioning between contexts, and feeling enough intellectual mastery to do so, seeking help of experts as needed.

help move them along the developmental continuum as effectively as possible.

Factors affecting student's learning include age maturation, immersion in university life, exposure to diversity, traditional coursework and experiential coursework (e.g., student centered and/or project-based PBL). Educators need to ensure students graduate with an expanded set of learning strategies and with the ability to think contextually and to generate knowledge. Although it is rare for students to have reached this level of ability after four years of university [8, 10], it is the goal of student development scholars and many educators. It is also standard practice in architecture, where students are typically not permitted to continue past second year unless they have demonstrated significant ability in contextual thinking. Therefore, university leaders can help promote development by getting architecture and design faculty engaged in helping teach engineers, as is the case in innovative institutions today.

Subsequent to Perry, other scholars have broken away from stage models. Although the study reported in this paper relies most heavily on theories that assume fairly step-by-step progression, other models are also available that do not assume such stability or linearity. For instance, Schommer-Aikins conceptualized development to occur along several parallel but independent paths [39]. Questioning the evidence for stages, Hammer and Elby suggest that rather than achieving a series of discrete steps, students develop a set of epistemological techniques, or 'resources', for operating in varied contexts [40]. The challenge is for individuals to develop a full range of strategies and learn to identify situations where each technique can be applied appropriately to achieve positive results. Thus, it is not the sophistication of the technique that matters, it is how well matched the technique is to the unique context in question.

Kuhn, Cheney, and Weinstock believe that development is domain specific and that individuals can develop at different rates in different domains. They have identified five specific domains: personal taste, aesthetics, values, social truths, and physical truths [41]. They also developed an inventory for assessing development in each of these domains.

In this paper, we draw on the descriptions of thinking provided by Perry, and others who use similar, fairly linear, schemes. We recognize the importance of even the more simple skills, but we also realize that some techniques and conceptualizations of knowledge are more difficult to achieve than others. Our study focuses on identifying instances where individuals make a break-through discovery that allows them to understand more sophisticated ways of thinking.

Perry ultimately developed a system for training evaluators to review interview transcripts and assign numeric values based on the level of development reflected in the students' responses. The rubric in this paper takes a different approach. It overlays two sets of theories (those regarding design thinking and epistemological conceptualizations) as a means for helping educators quickly evaluate design students' ways of thinking.

2.3.3 *Design-related development theories*

'Design researchers' seek to understand methods that designers use, describe these methods scientifically, and replicate them in humans and computers. Their research investigates how people assign purpose and meaning and how they compose, arrange, structure, and value things and systems [42]. The field's first studies sought to identify rational criteria for decision-making. Over time, design researchers have investigated: user participation in the design process, collaborative and multi-disciplinary design techniques, management science, cybernetic practices, computer-aided design, evaluation of building performance, and cognitive aspects of design activity [43].

Scholars have developed stage theories to describe the progression from novice to expert. A learner who begins completely naïve of a subject can progress from novice to advanced beginner, and then to levels classified as competent, expert, master, and—ultimately—visionary [44]. Although each level represents a distinct way of looking at issues, a designer can actually approach different issues from different levels of expertise within a single project, similar to the resources model described above [39, 45]. David Crismond incorporated novice-to-expert thinking in a rubric he disseminated at a design educators' conference in 2008. The rubric operationalizes the design process. It defines low-level design skill, and compares it with higher-level design ability. Each row represents a contrasting pair of statements about a specific type of strategy. Crismond's *Design Strategies Rubric* defines critical phases of the design process (in one column) and provides criteria for assessing an individual's learning progression from novice to competent or 'informed' (in another column). It can also be used to assess a student's performance [46]. Crismond teaches science educators, but he designed this rubric to work in settings where people are engaged in all types of creative work [16]. It is applicable to artistic and scientific design, he says.

2.3.4 *Hybrid rubric*

The lead author of this paper, Shannon Chance, created an *Epistemological Development Rubric for Designers*. The rubric is provided below (see Table

2) and a detailed description of the tool's development is available elsewhere [47]. In brief, the *Epistemological Development Rubric for Designers* delivers a synthesis of theories discussed above regarding epistemological development and design strategies. It superimposes various epistemological theories atop the *Design Strategies Rubric* created by Crismond [16].

The hybrid *Epistemological Development Rubric for Designers* provides educators with a tool for evaluating the types of behaviors typically exhibited by people learning design. The rubric can help teachers and researchers identify changes in students' epistemological understandings and design thinking skills.

Each cell/definition set in Table 2 describes student behaviors typical at various phases in the design process. Phases of design are listed in the left-hand column. Behaviors indicative of beginning designers are identified in the middle columns while the right-hand column describes students who are facile with contextual thinking. These more experienced (or informed) designers are able to address more complex, ill-defined problems. Prior theorists' descriptions are coded in this rubric so that each definition can be traced back to its original source. In disseminating this rubric, we aim to help educators become more aware of when and how students are developing epistemologically and when their misconceptions might be hindering design achievement.

3. Design of exploratory study

In this research project, we wanted to use the *Epistemological Development Rubric* as a tool for understanding and assessing students' blogs and vice versa. This constitutes an exploratory study that has yielded preliminary results, reported here, that warrant further investigation.

3.1 Research questions

In this project, we wanted to identify instances of student growth resulting from of this collaborative design studio course. We developed a number of research questions.

- (1) To what degree do blogs from a highly open-ended PBL project provide evidence to support. . .
 - . . . existing theories regarding the design process?
 - . . . existing theories regarding epistemological development?
 - . . . our assumptions regarding overlaps between design and epistemology theories?
 - . . . our assumptions regarding the efficacy of

collaboration and hands-on activities in engineering education?

- (2) To what degree does the *Epistemological Development Rubric* warrant further use and/or development?
- (3) To what degree can *template analysis* help us study such topics effectively?

3.2 Methodology

Our study used template analysis to help determine the level of fit between the content of the blogs and the template. We aligned our epistemology (constructivist), theoretical perspective (interpretivist), methodology (template), and methods (comparing blog texts to rubric definitions) as Crotty recommended, "to help ensure the soundness of our research and make its outcomes convincing" [48, p. 6].

In this study, the underlying epistemology is constructivist in that our goal is not to find some universal, objective truth about the phenomenon we study but to develop and offer the reader an understanding of it that we have carefully analyzed and considered. Aligned with this epistemology is an interpretivist theoretical perspective guiding our research study. We do not attempt to verify or deny a hypothesis. Instead, we offer an interpretation—again, careful and considered—of what we observed and measured. Unlike a very open-ended discovery oriented project that one might find in phenomenology [49], the approach taken here involves verification. We are testing data against *a priori* theories rather than seeing what theories can emerge from the data. We come to the study with a lens through which we examine the data. Using a different lens will reveal different issues.

Template analysis is suitable for use with a wide variety of epistemological approaches [50]. It has been used successfully in qualitative psychology research; examples abound in research on organizational, business, and health care management [51]. Template analysis is frequently implemented in studies using Grounded Theory and Interpretative Phenomenological Analysis (IPA), although it is not always explicitly labeled as such [50]. It is not appropriate for studies that adopt a radical relativist stance, but at the other end of the spectrum, it is quite appropriate for use with *a priori* codes [50]. It is highly practical for studies that have large sample sizes due to its flexible approach, and Nigel King says studies involving 20–30 cases are common [50].

In our situation, the template was the *Epistemological Development Rubric for Designers* described above. Here, the template grounded the assessment. We acknowledge that the template filtered what the researcher saw and considered. In using the template, we did not necessarily seek to identify *all*

Table 2. Epistemological Development Rubric for Designers [47]. The origin of each item can be determined using the associated number (Perry = 7, Baxter Magolda = 8, Belenky et al. = 9, Love & Guthrie = 10, Crismond = 16, items by the author of the rubric = 0).

Revolutionary Restructuring¹ The Great Accommodation⁴			
<ul style="list-style-type: none"> • Perry⁷ → • Baxter Magolda⁸ → • Belenky et al.⁹ → • Love & Guthrie¹⁰ → 	<ul style="list-style-type: none"> • Dualistic Thinking⁷ • Absolute & Transitional⁸ • Received & Subjective⁹ • Unequivocal¹⁰ 	<ul style="list-style-type: none"> • Multiplistic Thinking⁷ • Independent⁸ • Procedural⁹ • Subjectivist¹⁰ 	<ul style="list-style-type: none"> • Relativistic & Committed Thinking⁷ • Contextual⁸ • Constructed⁹ • Generative¹⁰
<ul style="list-style-type: none"> • Crismond¹⁶ Phase of Design ↓ 			
I. Exploring the Challenge¹⁶	<ul style="list-style-type: none"> • Little exploration.⁰ • Makes brief reading, overlooks research, & makes decisions prematurely.¹⁶ • Looks for answers in external authorities. • Reflects awe in authority figures (received) OR reflects belief that his/her own knowledge is superior to others (subjective).⁹ • Sees truth & knowledge as: external, not open to questioning, universal and context-free, constant, and the same everywhere.¹⁰ 	<ul style="list-style-type: none"> • Seeks to map a process for achieving results.⁰ • Conducts some research.¹⁶ • Sees instructor as providing context for exploration of knowledge.⁸ • Emphasizes procedure with evidence of doubt (separate) OR evidence of belief, empathy, and care (connected).⁹ • Expresses an increased sense of uncertainty, ambiguity, & complexity.¹⁰ • Often adopts the view that all views are equally valid and that opinions are sources of truth.¹⁰ 	<ul style="list-style-type: none"> • Plunges into exploration.⁰ • Embraces <i>process</i> as a means for generating new ideas.⁰ • Holds off on making decisions until challenge has been explored from many angles.¹⁶ • Integrates existing info & research. • Conducts quick studies/tests to explore a range of ideas.¹⁶ • Reflects personal integration of info based on rational inquiry (includes setting goals, asking what is needed as well as how things work & why).⁷ • Integrates personal experience & reflection (perhaps generating new paradigms, insights, and judgments).⁷ • Shows evidence of listening to others without losing ability to 'hear' own voice.⁹
II. Generating, Building, and Communicating Ideas⁵	<ul style="list-style-type: none"> • Tries to look for keys in professor's statements.⁰ • Works in linear steps OR haphazardly works on whatever happens to emerge.¹⁶ • Learns through imitation, by acquiring information & competence from professors.⁷ • Reflects a utilitarian approach to knowledge.⁸ • Works to receive and/or master knowledge (absolute) & gradually begins to accept that some knowledge is uncertain.⁸ • Seeks to receive & reproduce knowledge but lacks confidence in ability to create new truths (received) OR insists something is true without deeply questioning it (subjective).⁹ 	<ul style="list-style-type: none"> • Begins using rules-of-thumb to help make choices.¹⁶ • Acknowledges multiple viewpoints & considers how to determine which is "best."⁷ • Still sees knowledge as coming from external authority—from asking what others expect & how to do it.⁷ • Views knowledge as mostly uncertain.⁸ • Constructs an individual point of view but does not consistently seek to provide supporting evidence for it.⁸ • Emphasizes procedure & impersonally applies a procedure for establishing truth (separate) OR draws from personal experience (connected).⁹ 	<ul style="list-style-type: none"> • Proposes personal goals (or additional personally relevant requirements) for each new project.⁰ • Reflects idea fluency & uses problem-solving strategies in any order, as needed.¹⁶ • Uses words, drawings, & models to explore ideas & show how parts connect & inter-relate.¹⁶ • Uses diagnostic vision, addressing problems & troubleshooting ideas.¹⁶ • Still recognizes multiple views but seeks congruence & simplicity.⁷ • Seeks new experiences (perhaps re-constructing past conceptions on the basis of new experiences, developing new paradigms, or creating new dialectics).⁷ • Sees legitimacy of knowledge claims as determined contextually.⁸ • Constructs individual point of view with supporting evidence.⁸ • Integrates objective & subjective thought (i.e., thinking and feeling).⁹ • Is an intimate part of what he/she knows.⁹ • Is articulate, self-aware, caring, & concerned (uses both separate & connected thinking).⁹ • Realizes power to generate, produce, author, or originate (knowledge, future, self, creations, truths⁴, or realities).^{10, 0}
III. Testing and Evaluating Solutions, Reflecting on Practice⁵	<ul style="list-style-type: none"> • Avoids rigorous testing.⁰ • Shows very little awareness of his/her thought process.⁰ • Values grades over learning.⁰ • Pays too much attention to simple pros & cons.¹⁶ • Has an unfocused way of testing & troubleshooting.¹⁶ • Shows little self-reflection or monitoring of action.¹⁶ • Seeks clear means to concrete ends.⁷ • Tests only against stated requirements (received) OR assumes validity subjectively without rigorous testing (subjective).⁹ 	<ul style="list-style-type: none"> • Tests multiple options but does not rigorously question the established processes for testing.⁰ • Reflects emerging awareness of own thought process.⁰ • Begins to probe trade-offs & benefits.¹⁶ • Values professors who promote independent thinking & facilitate exchange of opinions.⁸ • Emphasizes procedure with evidence of critical thinking.⁹ • Listens to reason with implicit adversarial or impersonal tone (separate) AND/OR displays trust & patience in process (connected). At this stage, the student may flip back & forth between separate and connected thinking.⁹ 	<ul style="list-style-type: none"> • Shows clear awareness & enjoyment of own thought process.⁰ • Reflects a balanced system of weighing benefits & trade offs in making decisions.¹⁶ • Approaches design as a managed, iterative process.¹⁶ • Uses feedback to improve ideas.¹⁶ • Practices reflective thinking, keeping tabs on design work in a metacognitive way.¹⁶ • Seeks competence in work & social roles.⁷ • Uses knowledge to achieve internalized standards of excellence & to serve society.⁷ • Asks key questions & poses key dilemmas.⁷ • Fosters personal experience & personally generated insights.⁷ • May confront & seek to reconcile paradoxes & conceptual conflicts.⁷ • Sees role of professor as creating learning environment by: endorsing contextual application of knowledge, helping students evaluate various perspectives, providing opportunities for mutual critiques between students & instructors.⁸ • Is inherently reflective.⁹ • Struggles to find balance.⁹ • Reflects "passionate" knowing.⁹ • Practices metacognition¹⁰ by reflecting on & critiquing his/her design process & outcomes.⁰

themes that could emerge from the data. Instead, we grounded our readings in existing theories. This of course, focused (and therefore limited) what we found—to topics and theories included in the template. King justifies this, insisting that the point of the template and the coding is to help the researchers interpret the text and produce an account or interpretation that reflects the richness of the data.

In this study, after conducting preliminary rounds of analysis and coding, the lead author sought to identify patterns in the data and then considered relationships to other type of data we had on hand. As this was an exploratory study, we did not attempt exhaustive analysis, but instead sought to derive sound understanding of learning that had occurred. We wanted to assess (a) the value of the rubric as a tool for evaluating student learning as well as (b) the usefulness of blogs as sources of data for future research on epistemology. The overall process followed this general sequence:

1. Using a blank copy of the rubric, create a file for each individual student.
2. Analyze each student's blog chronologically. Consider the blogs from each team in relation to the others in the same team.
3. On the analysis file created for each student, note the students' field and any biographical information provided.
4. Review the text and images included on each student's blog, one blog at a time.
5. Identify as many statements as possible that relate to design and/or epistemology.
6. Locate the definition on the rubric that best represents the content of each statement.
7. Paste a copy of the statement into the rubric, directly under the definition.
8. Check to make sure that the statement is representative of the column under which it has been placed.
9. When all text in the blog has been coded, zoom out and assess patterns. (Do most comments fall under one column, or within a specific scholar's theory? Is there evidence of change over time?)
10. For each blog, summarize the results as well as any patterns that emerged.
11. Create a master file for each team that includes a summary statement for each team member, to facilitate comparison.
12. Review the coded rubrics by group, underlining specific statements that help answer our research questions.
13. Summarize themes in the data related to the research questions.
14. Triangulate results of blog data by comparing them with other data collected by the university.

15. Reflect upon results and generate findings, then develop ideas for future research.

3.3 Data sample

The University of Michigan offered SmartSurfaces over a period of three consecutive years (as one of a suite of nine multi-disciplinary, team-taught courses that received special funding). At the outset of the course each student granted informed consent, thus allowing future researchers to analyze content and report findings. The University's Institutional Review Board approved analysis of data for this study.

As part of SmartSurfaces, students were required to reflect upon and document their learning processes on publically accessible blog sites during the semester. This exploratory study involved analysis of 18 of approximately 72 blogs created by students over the three years of the SmartSurfaces course. We analyzed all blogs produced in 2010 (the middle year of the course) that were still accessible via the Internet. We selected 2010 for this exploratory study because the teaching techniques were firmly established and the student group was mainly undergraduate students (whereas 2011 included Master of Architecture students who are typically more mature and may have included a disproportionate number of relativistic thinkers).

A single student authored each blog across the span of a semester. The blog authors in our sample were college juniors and seniors who were majoring in art and design, architecture, and materials science engineering. Our data sample included blogs from all four 2010 teams. We believed that by qualitatively assessing the reflective blogs written by students during the course, we could better judge students' claims (on the University's CRLT survey mentioned previously) that they learned various skills.

4. Results of exploratory study

Analyses revealed that many of the student bloggers, who were majoring in architecture, art and design, and materials science engineering at a large public institution in the American Midwest, approached design in sophisticated and well-informed ways, as defined by David Crismond [16]. However, a majority of students approached the online writing assignment in a straightforward manner—reporting chronological facts without providing deep critique of their personal thought processes.

Those who did use the writing assignment to prompt reflection also generated for themselves a deeper understanding of what they were experiencing and how they were making decisions in the SmartSurfaces course. These students used their

blogs to spur their own metacognitive thinking. This is noteworthy for educators because metacognition by students is a key indicator of sophisticated thinking with regard to both design process and epistemology. Informed designers, for instance, practice “reflective thinking, keeping tabs on design work in a metacognitive way” [16, p. 1]. Metacognitive behaviors also suggest an individual has made ‘The Great Accommodation’ [10] or accomplished ‘Revolutionary Restructuring’ [7]. After crossing this threshold, the individual is capable of making decisions in context and can do so in a consistent and ongoing basis. This impressively high level of development was reflected in a number of the SmartSurfaces blogs. This is significant because theorists agree such development usually isn’t achieved during the undergraduate years [8, 10].

By comparing blog statements to the epistemological rubric, we could investigate design thinking and epistemological development. We generated additional results by triangulating data from multiple sources. Below, we discuss each of these topics in turn.

4.1 Results regarding design thinking

In assessing students’ design thinking, we found all students had experienced informed design thinking. This is because each student had either: (a) entered the course equipped with effective design-thinking skills or (b) was part of a team that utilized informed design strategies. On the whole, the students from the non-design major (i.e., materials science engineering) arrived in this course with weaker design skills. Their blogs describe their experiences learning design process and collaboration. The following example of mid-level development was provided by an art and design major. It reflects: (a) an emerging awareness of one’s own thought process and (b) intentionally delaying decision-making until after exploring ideas.

“After discussing our table idea for a bit, it made us recall an idea that we tinkered with the night before. We, as a group, have a habit of settling on the ‘first’ idea that seems feasible and that we get excited about. So to break that habit, while constructing our cube, we did a brainstorm session to see if there were other possible ideas we could explore or do instead. From this meeting we generated this idea about a cloud. . . .”

With the help of peers, the student quoted above recognized that her team had been fixating on ideas and making premature decisions after too brief a reading of the problem. As a group, these students recognized the problem and began implementing more sophisticated strategies.

Some students’ reactions to their teachers illustrate novice-design thinking. The following state-

ment, from an engineering student, shows heavy reliance on professors and a focus on issues the teachers imposed rather than issues identified through a process of self-critique.

“When the professors saw everyone’s projects last Thursday, [one professor] was surprised that we didn’t all have working solar detector things, since he thought that was all they asked for. Maybe they should’ve made that more clear after interrogating every group about context and application each week for the previous assignment, because the result was that everyone had an application but their projects only kind of worked at best. While about half our group was in the sewing workshop, including me, the profs gave my group feedback. Apparently the general gist of it was to make things more ‘elegant’. It’s just so confusing and frustrating when for 3 weeks they say ‘WHAT’S THE CONTEXT? YOU NEED CONTEXT!’ and then we give them context and application and everything and then they’re like ‘what? context? we just wanted a pretty solar tracker!’ So we met in [the design lab] for a while and figured out how to make it more elegant. . . .”

On the other hand, because students who are accepted to this university already have very high-level academic ability, even the most novice designers in this course caught on fairly quickly and were able to understand and follow the process of the experienced design students. They soon adopted effective design techniques described by Crismond [16]. Upon entering the course, novice designers were immediately exposed, by their peers and professors, to effective ways of navigating the design process. Novices learned by collaborating with more experienced designers, and experienced designers benefitted through exposure to other fields. As one novice designer explained:

“Working in a team is inspiring. Today, I started sketching and ideating an hour before our small group meeting. I got really down on our concept, since I felt there was nothing ‘smart’ about the surface(s) we were designing. My teammates’ definitions for ‘smart’ were much more open for interpretation. They were quick to stop me for dismissing an idea far before it was worth dismissing.”

This example shows the development of informed design strategies [16]. It provides evidence that the student can listen to others without losing her ability to hear her own voice—a critical feature of ‘constructed knowing’ [9]. Novices immediately experienced (and soon developed ways to describe) a range of effective design strategies, apparently due to extensive exposure to knowledgeable designers. For instance, in the 2009 survey, 100% of students in this course said their analytical and problem solving skills improved as a result of “faculty collaboration and exchange” and 75% of the respondents said that “differences in faculty viewpoints” increased their analytic skills [34].

4.2 Results regarding epistemological development

In assessing students' cognitive and epistemological development, we noted that all members of the class were seeking new experiences. Each student who enrolled in SmartSurfaces had willingly tackled a formidable challenge. This provides evidence that they were plunging into exploration and embracing process as a means for generating new ideas. Most seemed eager to reconstruct past conceptions in light of these new experiences.

Although some students initially lacked design experience, they were nevertheless interested in following the lead of more experienced designers because they wanted to learn design. Sometimes, this sparked significant 'ah-ha' moments. In the quote below, an engineering student who expressed resistance to others' ideas throughout much of the course described some sort of break-through moment that precipitated reflection and led to an important re-conceptualization. He appears to have made a significant break-through that is an important step toward 'Revolutionary Restructuring' and making the 'Great Accommodation.'

"I decided to learn [a 3-D digital modeling program named Rhino], taking any chance I could learn from the architects and art and design majors. To each I am very grateful. And I learned how to put together simple shapes as best I could. But I was learning how to create and it felt exhilarating. Much more alive and enticing than anything the college of engineering has thrown my way."

He proceeded to reflect upon past experience in his major:

"As engineers we learn theory. And theory is a clear divorce from practice. It is silly we even entertain the title of engineer. We are not good with our hands, nor are we good at innovation. We learn how to solve problems that have already been solved. Innovation only spews forth from empirically manipulating tangible things until they best serve a desired function."

His text is indicative of movement from the middle column (i.e., multiplicity) to the right-hand column (i.e., relativism) of the *Epistemological Development Rubric*. Growth is evident when these later statements are compared with less-sophisticated statements he made earlier in the semester, such as:

"The progression was not without its dilemmas. Our group became puzzled by function. Many an hour was lost to debate of the purpose of things. Eventually the topic of function was quelled by form. . . . But let us not forget the forms that did not survive past the few days. . . . I am conflicted with what other wonderful surfaces we could have crafted had one not emerged over all."

This early comment emphasized procedure while conveying a sense of doubt and a sense of separation from both 'what is known' and 'the process used to generate knowledge' [9]. Most students seemed much more connected to the design process from

the start. In addition, most students viewed the professors as setting the context for learning, not simply providing a gateway to external truth; therefore, these results have epistemological implications.

"Our team is excitedly moving forward with a positive, helpful critique and workshop under our belts. The critique was really more a series of suggestions and possibilities for what our project could become."

"I really appreciated the feedback from the instructors and classmates and after reverse brainstorming with [one of the professors] we will have many leads to follow for this coming Thursday. Personally I have been thinking about scale a lot more. What could we do with this shape if it was the size of a building or the size of a pea? The shape is so versatile that it actually could be applied on many different magnitude scales. Anyway, this class makes me think A LOT and it kind of tires me out, so I will let you know what's going on at a later date."

The quotations above reflect Baxter Magolda's definition [8] of contextual thinking in that both of the students viewed feedback from their professors and peers as a helpful guide to expanding their perspectives. The student blogs consistently describe: the value of learning from peers, sharing multiple perspectives, testing ideas, and making decisions in context. Teamwork, and the blogging process itself, seemed to help students reflect upon and hone their epistemological understandings and design strategies. They also appeared to help students integrate ideas across disciplines and, in some cases, across learning environments outside this class.

"I am a Student Coordinator for [an art class focused on] Creative Process and Collaboration. My job is to facilitate class discussion, provide support. . . . Yesterday, we asked the students to start thinking about what it means to create a 'Designed Experience'. Since I wasn't really sure myself, I developed my own definition. . . . In connection to SmartSurfaces, [this student leader realized that his team was engaged in] designing an experience. . . ."

In the quote above, we see that the Student Coordinator, and other individuals in the course on Creative Process and Collaboration, engaged in metacognitive activities. For the Student Coordinator, blogging prompted reflection and integration of learning [52]. The quote reflects very student-centered experiences. Overall, blogging seemed to help encourage students to integrate personal experience and reflection into their designs. The blogs indicate an emerging confidence in generating definitions, insights, and/or paradigms.

The author of the following statement is: asking key questions, posing key dilemmas, confronting significant discontinuities and paradoxes, and personally generating insights [7]. Integration of learn-

ing, across experiences and disciplines, is also evident [52, 53].

“For me in particular, this was a really good opportunity for me to put a lot of thoughts on the table that I have had for awhile now. When our team is so focused on just getting a project made or working, the specificities of working-methodologies can easily get put on the back-burner. It’s important for us all to remember, however, that this class isn’t all about making SmartSurfaces. It’s also about learning how to work as a member of a team with unique abilities that you’ve gained from your discipline. Incorporating this thinking into our [team] was crucial not only to making our team work better, but also to optimize what we all can get out of the class.”

A Materials Science Engineering student who was new to design provided the series of statements below. She appeared to bring sophisticated epistemological understanding to the process of learning design, and so her comments fell solidly into the right hand column of the rubric. She demonstrated contextual thinking and generative knowing despite the fact that she had just begun to learn effective design strategies. She was, nevertheless, able to understand and appreciate the design process she witnessed. The following statement shows she was learning to ‘hold off on making decisions until the challenge has been explored from many angles,’ a desirable skill defined by Crismond [16].

“I always want to have a plan that we can all stick to and follow because I thought it would make things more efficient. Maybe it does and maybe it doesn’t, but maybe being super-efficient isn’t always better. Letting something that follow[s] the basic criteria grow organically was really rewarding and the level of excitement after our solar tracker started moving was amazing.”

She also provides evidence of listening to others without losing the ability to hear her own voice.

“When someone tells me to cover a curve efficiently I immediately think polygons and lots of straight lines. . . you know, get the highest atomic packing factor possible, go with hexagons! But listening to the other members of the group I realize that not only would they not necessarily be the best, but also curved shapes might make a surface more functional and pleasing to the eye instead of the harsh shapes I was thinking of. We discussed different ways of exposing and covering from flipping and rotating to telescoping. . . this is about when the instructors . . . came over and said something along the lines of ‘Maybe there don’t have to be two stages in time, maybe it can be covered or exposed at different points in space.’ Hmmm. Why didn’t we think of that?”

Her narrative indicates she was already inherently reflective and capable of metacognition. She used these abilities to help herself develop understanding and skill in the realm of collaboration.

“There were definitely some positives and negatives in our team dynamic. . . , so first I will delve into the plusses. I liked how our team would bounce ideas off each other and build on the previous thoughts. It was also good that

we were all able to go down paths we were interested in to test the boundaries and limitations of different approaches that went along with the same theme. One thing that should be improved on for this week is decision making. I’m not sure if it was just that no one wanted to step on any toes or if we just weren’t confident in our own ideas, but it took the team far too long to pick a direction. I think this could be helped by thinking apart for a while and coming back to the group with a well thought out idea.”

The quote above also suggests a healthy understanding of the teacher’s role as a guide, rather than a gatekeeper of truth. The text reflects personal integration of information based on rational inquiry. It describes ‘setting goals, asking what is needed, how things work, and why.’

“What Does It Do? That is a good question. Our design is such an open platform we couldn’t decide. We couldn’t decide what sensors to use. We couldn’t decide what to make it do or how to react. No one wanted to commit to any one thing. This is why we decided to make our array of clusters very multifunctional... we decided not to decide, basically. We will have clusters of 5 modules. . . . What I would really like to see, though, is a hierarchy of sensors. Maybe the light sensor realizes that it is day time, so the motion sensor starts working and once it senses motion the little creatures start wiggling around and then stop if someone gets close or makes noise and close up.”

Not rushing to make decisions is an approach experienced designers take. This student’s statements also provide evidence of metacognition and show that, while she successfully recognizes multiple views, she also seeks congruence and simplicity. These characteristics typify high-level ‘relativistic’ thinking as defined by Perry [7]. Perhaps the most exciting discovery derived from her blog, however, has to do with the way she thinks about creation and knowledge generation. In describing the result of her team’s deliberation, testing, and model building, she explained:

“This is where, I think, our ideas started to become unique and take shape.”

“This was the first time I had ever made something that seemed to be an entity all by itself once it was plugged into an electrical source. It was really exciting and kind of changed the way I feel about design and creation. Instead of trying to make a very specific thing with the exact attributes that you want you can make something and then let it tell you what you have made. . . . [one of the professors] basically said the same thing during some of the presentations and I wouldn’t have really believed it until this project was done. This also hits on my weaknesses thus far in Smart Surfaces.”

In this case, the professors had introduced a bottom-up design process, where the designer creates something then names it and/or determines what use it might serve, as opposed to the typical top-down approach where the use is specified prior to design.

4.3 Themes apparent in the blogs

Across the sample, it was easier to find statements indicating development of brand new design strategies than of brand new epistemological understandings. In the course of our analyses, a number of patterns related to learning and development became apparent. As a set, these blogs described:

- Collaborative, peer-to-peer learning and teaching
- Contextual, generative ways of knowing (described by many, but not all, students)
- Reflection and metacognition (among many, but not all, students)
- Implementation of informed design skills
- Widespread ability to describe effective design behaviors
- Extremely high levels of student engagement
- Ability to connect ideas

The excerpts included in this paper help support these claims. By studying SmartSurfaces blogs, it is possible to develop solid understanding of the peer-to-peer learning and teaching that occurred. Such learning encompassed the sharing of discipline-specific ideas, technologies, and skills in addition to the development of more general skills.

4.4 Triangulation with survey data

We triangulated blog data with: (a) survey data collected by the institution and (b) summative evaluations collected by the SmartSurfaces teachers. The first of these provides students' self-assessment of how much they learned in comparison to other classes they had completed at the university. The second allowed for open-ended responses.

The survey was conducted only the first year SmartSurfaces was offered, 2009. In the survey, 12 students (of the pool of 24 who completed the course) provided quantitative data about their experiences in the course. The group reported making significantly higher gains in using systematic reasoning in approaching problems than reported by students in the comparison group (all other multi-disciplinary, team-taught courses at the institution). In all, 417 of the 634 students who enrolled in the university's suite of these special courses in 2009 completed the survey, with a response rate of 66% [54]. Twelve of the 417 had taken SmartSurfaces. Demographically, enrollment in these special courses mirrored the institution [54].

Interestingly, the SmartSurfaces students reported significantly fewer gains than the comparison group reported in connecting key class ideas with *other knowledge*. Yet, when the survey question was narrowed ask about connecting concepts *across disciplines*, positive responses from SmartSurfaces

spiked. In fact, 100% of the 2009 SmartSurfaces respondents said they developed 'more or much more' skill in 10 of the 21 items queried (see Table 3).

The students' blogs provide ample support for claims students made about their learning, included in the excerpts below (underlines added to highlight key concepts). In the culminating survey, students described high levels of learning, passion, and engagement—relevant to both design and epistemology.

"This was by far the best course I have ever taken at the University. The amount of work required for the class is ridiculous, but it is work put in voluntarily because of the passion we have for our projects. I've learned so much from this class, and it will likely affect my career."

"Craziest class ever. I have put in an obscene amount of work for this class but it was worth it. Had a great time building weird projects and collaborating with other students from other disciplines."

The SmartSurfaces experience was transformational in that it facilitated reflection about career path for several participants. Such decisions are not usually taken lightly.

"Best class I have taken at the university (in every way). Despite the lack of credits earned and lack of sleep acquired, I would take it again in a heartbeat. Multi-disciplinary majors really added a lot to learning different skills. Being thrown into a hectic environment head-first was a scary but worth-while and excellent experience. This class has changed what I want to do as a career and how I go about analyzing problems and issues. I wish everyone could take a class like this."

Transformation and change at the personal and epistemological level is revealed by the quotes directly above and below, both of which seem to reflect Revolutionary Restructuring.

"The class is completely changing the way I approach problems, and has changed the way I work in groups. The extremely large amount of time required for this class pushes everyone in the class to achieve a lot more."

This engineer is considering leaving the field, or branching out, in order to experience more team-based design and pedagogy:

"I am not only amazed by how much I have learned technically, but also about team design and dynamics. I really wish that there was more flexibility in the engineering curriculum to fit more classes like this into a schedule and still graduate on time. This class has truly inspired me and I am now considering a degree in divergent or experimental education."

Although this student desires more design studio work s/he appears to assume that nothing can be removed from the curriculum accommodate more of this kind of activity. This reflects the predominant traditional approach to engineering education. Such expressions appeared in the closing passages of many students' SmartSurfaces blogs. For instance:

This semester has been both frustrating and rewarding. This class was the most time intensive studio that I have taken thus far in my college career, and although it was not worth more credits than my other studios, it quickly became the most important because of all the learning opportunities I felt it presented. . . . I've learned a lot about the design process, and how to be as effective and efficient as possible especially while working within a multidisciplinary team. I was also exposed to a lot of different technology that I would probably otherwise not have heard of, let alone had a chance to experiment with. This added onto my skill set and will definitely affect my future projects. There were frustrations along the way, particularly while designing, because a lot of the time the

designs were based on the electronic components, which I did not know a lot about and could not contribute to as much as I would have liked. But these also proved to be learning opportunities for smaller, but important tasks such as wiring and soldering. Overall, I think our smart surface was successful in that we experimented with and implemented a smart material for the biomimicry story we were trying to achieve. . . . It feels as if this particular learning experience is not over. . . . I know I have learned a lot in this class, and will implement the skills I have been building for the last couple of months in my future projects, but it will not be the same because of the rich learning environment and the professors as well as peers that I was able to work with.

Table 3. Skills development in the University of Michigan's multi-disciplinary, team-taught courses [34]

Compared to other courses you have taken at the university: <i>How much did you develop the following skills during this course?</i>	More or Much More than other courses	Same as other courses	Less than other courses	Compared to the eight other multi- disciplinary team- taught courses
Critical (n = 12)				
• Drawing on multiple perspectives in addressing problems or issues	91.6%	8.3%	0%	
• Making connections between major concepts from different fields of study	100%	0%	0%	Significantly Higher
• Identifying the components of a problem or issue	91.7%	8.3%	0%	Sig. Higher
• Identifying the data needed to solve a problem or answer a question	75%	16.7%	8.3%	Sig. Higher
• Investigating complex systems	83.3%	8.3%	8.3%	Sig. Higher
• Formulating good questions	75%	16.7%	0%	
• Choosing the appropriate method (or mixture of methods) to solve a problem	72.8%	18.2%		Sig. Higher
• Clarifying an unstructured problem	100%	0%	0%	Sig. Higher
• Considering a broader context when decision-making and problem-solving	100%	0%	0%	Sig. Higher
Oral (n = 12)				
• Identifying multiple perspectives when listening or working with a group	91.7%	0%	0%	Sig. Higher
• Participating effectively in group discussion	100%	0%	0%	Sig. Higher
• Conveying your ideas effectively	91.7%	8.3%	0%	Sig. Higher
• Checking to see if your thoughts are understood	100%	0%	0%	Sig. Higher
• Checking to see if you understand others' thoughts	100%	0%	0%	Sig. Higher
• Relating to people with backgrounds different from yours	100%	0%	0%	Sig. Higher
• Listening to audio or video media critically	16.6%	58.3%	8.3%	Sig. Lower
Reading and Written Communication (n = 12)				
• Reading critically	16.7%	58.3%	25%	Sig. Lower
• Being able to read sources from multiple disciplines	58.4%	25%	8.3%	
• Developing research strategies	41.7%	41.7%	16.7%	
• Being able to integrate diverse material in writing	41.6%	50%	8.3%	Sig. Lower
• Being able to state and defend a position using relevant evidence	41.6%	50%	0%	Sig. Lower
• Being able to identify and respond to key objections to an argument	58.4%	33.3%	0%	
• Being able to write persuasively	0.0%	58.3%	25%	Sig. Lower
• Being able to write concisely	16.7%	41.7%	33.3%	Sig. Lower
• Using scholarly and professional sources	25%	41.7%	25%	
• Using internet sources critically	33.3%	66.7%	0%	
• Reading to extract key information	25%	50%	16.7%	Sig. Lower
Thinking Creatively (n = 12)				
• Willing to change your mind	91.7%	8.3%	0%	Sig. Higher
• Being open to others' points of view	91.6%	8.3%	0%	Sig. Higher
• Planning	91.6%	8.3%	0%	Sig. Higher
• Analyzing problems in a way that considers unusual alternatives	100%	0%	0%	Sig. Higher
• Working through obstacles	100%	0%	0%	Sig. Higher
• Being able to critique others	91.7%	8.3%	0%	Sig. Higher
• Being able to receive feedback and criticism	100%	0%	0%	Sig. Higher
• Producing work of your own design	75%	16.7%	8.3%	Sig. Higher

5. Discussion of results

Using the *Epistemological Development Rubric* helped our team identify cases where learning occurred as a result of experience in the collaborative design studio. Student blogs helped us test and evaluate the rubric and, in reciprocal fashion, the rubric helped us understand and assess the content of the blogs.

The blogs we analyzed support claims that collaborative, hands-on, design studio pedagogies can foster noteworthy development among students. Within our sample, many engineering students who had no previous design experience were able to identify and describe effective design behaviors, strategies, and patterns of thinking. Through our analyses, we were able to learn about how students' thinking evolved over time, why they made the design choices they did, and how collaborative and hands-on aspects of the class prompted learning.

5.1 Support for design theories

The data provided solid evidence to support existing design theories. There was one exception, however, which involved the 'phases of design' appearing in Crismond's original matrix. We found that in a design project of any complexity, behaviors described in all three phases of the rubric occur and re-occur throughout the process—they will not be relegated to just the beginning, middle, or end as suggested in the original rubric.

Crismond's *Design Strategies Rubric* was a pilot version that David Crismond disseminated at the 2008 National Conference on the Beginning Design Student [16] that Shannon Chance utilized in creating the *Epistemological Development Rubric for Designers*. Crismond continued to refine his rubric in collaboration with Robin Adams, and the duo recently published a new version in the *Journal of Engineering Education* [55]. In the intervening period, Crismond permitted Chance to include the pilot version in publications for university planners [46] and engineering educators [47].

The premise, structure, and specific definitions used in the pilot version of Crismond's 2008 rubric remain largely unchanged. However, in the 2013 publication of the *Informed Design Teaching and Learning Matrix*, Crismond and Adams removed the phase structure all together [55]. The results of our analyses support this change. Our study helps extend the validity of Crismond's rubrics by testing them against authentic data. Crismond and Adams' new rubric also adds two columns, which are helpful to teachers who want to use the theories to structure assignments and plan activities.

5.2 Support for epistemological development theories

Many SmartSurfaces students indicated they developed new design skills and approaches as a result of working with experienced design students and, in key cases cited above, some students also changed their ways of thinking about authority, authorship, creation, and/or knowledge-generation. Our analyses revealed several cases where students experienced 'ah-ha' moments that altered their perceptions. In this way, a number of the blogs reflected epistemological development as defined by William Perry [7] and others [8–10] in addition to development of domain-specific skills related to design as per David Crismond [16].

5.3 Implications for research and teaching

Finding correlations between design and epistemology development was crucial to confirming assumed relationships and to justifying the need for further research. Our analyses indicated Shannon Chance's rubric holds merit and that the overlap between these two sets of theories warrants further investigation. In its existing form, Chance's *Epistemological Development Rubric for Designers* may help educators understand and foster development of students' epistemological and design thinking skills.

The rubric represents a first step in connecting theories of design and epistemological development. Results indicate there is a good degree of correlation between these two sets of theories. The rubric provided a useful framework for assessing blog data, but our exploratory work indicated some items could be combined particularly where existing theories of epistemology have common themes. Future versions of the *Epistemological Development Rubric* should incorporate the changes reflected in Crismond and Adams' revised matrix [55] and any new student development theories that have emerged since its creation.

In addition, it might be helpful to analyze blogs using template analysis with each construct (design and epistemology) individually and then look for overlaps between the two templates. This could help confirm correlations between the constructs. Moreover, once an important statement has been identified to fit a definition on the rubric, that same statement could be evaluated against each definition in the rubric. This would allow us to identify patterns and, ultimately, to combine similar definitions, streamline the rubric, and identify relationships between the various theories. We might also want to study relationships between the grades students earned, or the professors' assessment of innovative work produced in the class. Knowing which groups were considered to be innovative

could help us determine if there is any correspondence between innovation and epistemological development as defined by prior theorists.

Our analyses provide support for existing cognitive and epistemological theories regarding student development. On the other hand, our findings indicate that many students in this course had reached a higher level of epistemological development than theorists believe is common among college undergraduates. All of the students in the 2010 SmartSurfaces class were juniors or seniors from a highly competitive, top-tier institution in the United States. They reflected higher-level development than the younger college students included in Candy Carmel-Gilfilen's [38] 2012 study, who were studying architecture and interior design.

Future research could ask if the rubric aligns appropriately with other tools for assessing development along Perry's schema. Follow-up work could ascertain the general level of epistemological development among architecture students and could explore claims made by Boyer and Mitgang about the efficacy of architectural education [1] by using a variety of empirical methods. Such work could help determine what percentage of architecture students make the Great Accommodation before graduating and how they typically achieve it.

Students in our sample—all of whom voluntarily registered for a highly challenging non-required course—were unlikely to reflect dualism (the left hand column of the rubric). There were very few instances where students looked to external authorities/professors for simple answers (indicative of dualism) or expressed belief that their own subjective knowledge was superior to that of others (i.e., multiplicity).

A number of (non-design/engineering) students entered this course with low-level design skills, and initially showed novice design approaches—and thus had initial tendencies to pay too much attention to simple pros and cons, exhibit an unfocused way of testing and troubleshooting ideas at the outset, or showed little self-reflection and monitoring of action—but such issues did not persist long. The collaborative design and blogging aspects of the course provided those students who were new to design with a plethora of models for iterative decision-making and tools to prompt metacognitive reflection.

For students who did fall into the middle column (i.e., multiplicity), this class seemed to provide a healthy challenge. They voluntarily faced uncertainty, ambiguity, and complexity. The course clearly improved their design thinking and it had some positive effect on several students' epistemological development as well.

On the one hand, design strategy and epistemo-

logical thinking may be two separate constructs. However, it is possible that design thinking is actually a subset (or one specific domain within) epistemological development. Our analyses indicated a student could be advanced in the construct of design thinking but not in the broader construct regarding epistemological development. The study of epistemological development does include some discussion of development in various domains; it is our belief that an individual can exhibit sophisticated thinking in some domains (such as personal values or spirituality, for instance) while at the same time displaying more elementary thinking in other domains (such as aesthetic values). This belief is consistent with research by Kuhn, Cheney, and Weinstock [41].

Our results lend support to two models mentioned earlier that were not used in the development of this rubric. The first theory posits that development occurs simultaneously along multiple independent yet parallel paths [39]. The second, the resources model, posits that as students develop various strategies, they also learn how and when to effectively apply each—and that this occurs in a non-linear fashion [40]. The open-ended student-centered context of SmartSurfaces prompted students to develop a wider array of skills. They got to practice matching design skills to specific contexts and applying them. The parallel development model and the resources model both merit consideration in future iterations of the *Epistemological Development Rubric for Designers*.

The blogs also shed light on peer-to-peer learning. Because the students worked in multi-disciplinary groups of six, it was possible for us to compare and contrast individuals' interpretations of similar events. This would make it possible to assess differences by discipline and level of design experience. In future iterations we could, for instance, count the number of times peers were mentioned in other students' blogs and analyze the statements for tone, content, shared interpretation, and implied learning.

6. Conclusions

Cooperative learning formats can be highly effective for teachers and students alike—particularly when they involve hands-on projects and multi-disciplinary teamwork. Collaborative, trans-disciplinary, team-taught studio education is the hallmark of the University of Michigan's SmartSurfaces course, and the blogs that students produced for the course provide proof of the students' learning and engagement. Data from student blogs and surveys helped the authors of this study confirm the applicability of various theories about design

and epistemology. The results reported above indicate open-ended, collaborative hands-on design assignments can facilitate impressive learning gains.

People involved in architecture and engineering can undoubtedly learn from each other. For engineering lecturers seeking to implement ill-structured design problems in their courses, teaching alongside architecture faculty (who are accustomed to studio teaching and to assigning projects that have unpredictable outcomes) can ease the transition from teacher-centered to learner-centered approaches. In the process of team teaching, architecture professors can model effective teaching behaviors and help structure project assignments. In the process, these architecture teachers have the chance to acquire or brush up on technical knowledge and learn to tutor students in group-work skills, since engineering educators are typically more adept at providing tools, guidelines, methods, strategies, and/or processes for group-based learning. Such give and take is evident in the SmartSurfaces class at the University of Michigan. There, the studio format—well understood by the architecture, art and design faculty—provided a valuable precedent that facilitated learning among students and teachers in engineering as well as in design-based subjects. Engineering's explicit exploration of student-centeredness can provide a model for teachers in other fields—including architecture—who frequently still put themselves, and what they themselves say, at the center of the classroom.

Nevertheless, the popularity of the studio format in architectural education cannot be denied, and using this type of format could possibly attract more individuals to study engineering. Hands-on, enquiry-driven, studio-based pedagogies have typified architectural education since the 1500s—helping students learn to integrate technical content knowledge with design creativity. Today, students seem to value the inventiveness and engagement they associate with architectural study and practice, and many young people flock to architecture and design programs even in weak economies, when jobs in these fields are scarce. Although engineering can provide similar outlets for creativity, its educational programs struggle to attract enough students and it is not normally perceived as a creative discipline. Perhaps this should change. Providing engineering students and teachers with experience in studio-based learning can be a positive step forward.

This study provides evidence of student development that occurred by applying design studio pedagogies to non-design fields. Data from blogs and surveys indicate high-level student engagement and instances of collaborative learning and teaching, knowledge generation, reflection, metacognition,

and systematic reasoning. The data describe students' emerging ability to: connect ideas, describe effective design behaviors, and use informed design strategies. The artifacts students created during the multi-disciplinary SmartSurfaces class lend support to claims they made during exit surveys about their learning. Blog text supported students' claims (made via survey) that they had developed more skill in SmartSurfaces than in standard courses. The triangulated data reflect immersion, passion, and transformational learning, describing change at the personal and epistemological level and students' increased desire for learning through collaboration and design. Students without prior design experience were able to enact effective design processes and skills. Their thinking evolved over time, and collaborative design aspects of the class prompted learning.

Through our analyses, we found evidence to support epistemology-related theories grounded in Perry's work as well as design theories embedded in the *Informed Design Teaching and Learning Matrix* as published in 2013 by Crismond and Adams. Correlations among these theories were evident, justifying the case for additional research. The *Epistemological Development Rubric for Designers* represents an initial step in connecting theories of design and epistemological development. We found it has useful qualities and it warrants further investigation.

Most strikingly, the data analyzed in this study indicate that many students in this course had reached a higher level of epistemological development than theorists believe is common among college undergraduates. Understanding how students achieve Revolutionary Restructuring in studio- and problem-based learning can contribute valuable new insight to the literature on engineering education as well as student development theory. Assessing design skill alongside epistemological development can help educators understand how to assist students in achieving meaningful, high-level growth among more students. By becoming more aware of how development is occurring in general and within specific classrooms, instructors can tweak their own behaviors and improve their pedagogies.

Acknowledgements—This work was funded, in part, by a Marie Skłodowska-Curie Actions (MSCA) individual fellowship from the European Union (Call identifier FP7-PEOPLE-2013-IIF, Project 629388, Project acronym: REESP, Project title: Re-Engineering Europe's STEM Pipeline). Thanks to Dr. James P. Barber, who assisted with a conference paper early in this study, Dr. David Crismond for sharing his rubric and allowing past publications of it, and the University of Michigan for granting ethics approval for this work. Anyone interested in doing PhD or post-doctoral studies to extend the work described in this paper with Shannon Chance is invited to contact her at shannon.chance@dit.ie or smchan@wm.edu

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Shannon Chance is a Marie Curie Research Fellow at the Dublin Institute of Technology following a Fulbright Fellowship in Ireland and 15 years at Hampton University, where she was a tenured Professor of Architecture. Shannon has also taught as an adjunct associate professor at The College of William and Mary and has served as a lecturer at Virginia Tech. Her teaching areas include architectural design and theory, environmental sustainability, urban design and theory, and educational planning. She has administered two-dozen travel programs in the USA, Europe, and Africa for university students. Shannon is a licensed architect and LEED Accredited Professional who has authored over 59 peer-reviewed publications, delivered conference presentations and over 55 other public lectures, and secured over \$.57M in grants and sponsorships to conduct educational research and training programs. She received a Ph.D. in Higher Education from William and Mary and two degrees in architecture from Virginia Tech. She has served on seven visits of the National Architecture Accrediting Board and recently chaired a visit.

John Marshall is the Director of the MDes Integrative Design program and an Associate Professor at the Penny W. Stamps School of Art & Design; an Associate Professor at the Taubman College of Architecture + Urban Planning; both at University of Michigan. His creative and scholarly work is design research that results in both exhibitions and publications. His research interests include: tangible interaction; design methods; and cross-disciplinary collaboration. John's studio practice involves a recursive process where multiple stakeholders work together to realize shared goals. Since 1998, John has co-directed rootoftwo, LLC. Recent projects have been featured in Wired, Fast Company, The Guardian, Dezeen, and Studio International. From 1999-2003 John worked in product development at Evenflo Company, Inc. He has degrees from Robert Gordon University (Ph.D.), Manchester Metropolitan University (MA), The Ohio State University (MFA), and Glasgow School of Art (BA). He is currently writing a textbook 'Introducing Hybrid Design' for Routledge.

Gavin Duffy has been working as a faculty member in the School of Electrical and Electronic Engineering Systems in the Dublin Institute of Technology since 2002. Prior to joining DIT he worked for several years for engineering design consultancies as both a chemical engineer and control systems engineer. He now delivers modules on chemical technology, instrumentation, automation, and control engineering and has been using project-based learning since 2005. His research activity is in the area of engineering education and is a member of the CREATE research group at DIT. Current projects include spatial ability among engineering students, epistemological development, and how engineering education research is conducted.