Toward Epistemologically Authentic Engineering Design Activities in the Science Classroom

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Abstract

In recent years educators and educational researchers in the U.S. have begun to introduce engineering design activities in secondary science classrooms for the purpose of scaffolding science learning as well as supporting such general problem-solving skills as decision making and working in teams. However, such curricula risk perpetuating a misconception about the nature of engineering design, or technology more broadly, as being applied science, when in fact its nature is more complex and its relationship with science is reciprocal. Developing an understanding of technology itself is a major part of national science education standards. Based in situative and cognitive theories, this paper critiques assumptions of engineering design activities in science classrooms from the perspective of their alignment with an epistemology of professional engineering design. Analyzing alignment of professional and classroom practices will require thick descriptions of both realms. This paper contributes to such an analysis, drawing on philosophical and sociological accounts of engineering practice to develop a prototypical epistemology of engineering design to which classroom practice may be compared, or that may be considered in developing future classroom engineering design activities.

Introduction

In recent years educators and educational researchers in the U.S. have begun to introduce *engineering design* challenges in middle- and high-school (Grades 6-12) science classrooms. A common example is having students build model cars powered by balloon engines as a way to learn about force and friction. In these settings, engineering design is typically used to scaffold science learning, as well as to support such general education goals as decision-making and working in teams. However, positioning engineering design primarily as a tool for science learning runs the risk of misrepresenting the nature of engineering as *applied science*. In reality, the nature of engineering—its *epistemology*—is more complex. Scientific knowledge is but one of the resources required for engineering design. Furthermore, the relationship between science and engineering is more appropriately described as reciprocal, not uni-directional.

Understanding the nature of engineering design—more broadly, the nature of *technology*—is espoused by national, state, and local education standards as an element of technology literacy (Rutherford & Ahlgren, 1990; National Research Council [NRC], 1996; International Technology Education Association [ITEA], 1999; Wisconsin Department of Public Instruction [WDPI], 1998; Madison Metropolitan School District [MMSD], 2001). The socio-cultural conception of *literacy* foresees a natural continuity from participating in engineering design activities in school to participating in professional engineering practice and, more generally, in our rapidly changing technologically oriented society. Vygotskyian theory implies that students' beliefs and understandings about the nature of engineering will be shaped by the nature of the engineering activities in which they engage. It follows that to foster beliefs and understandings that will serve them beyond school, we must engage students in *authentic* activities in the classroom—activities aligned with real world practices. The flip side of the argument is that if we engage students in engineering design activities that misrepresent the nature of authentic practice, students will in effect be participating in something different than engineering design. A mild consequence of non-aligned activities is that they may do nothing to further students' technological literacy; a worse consequence is that students may develop inaccurate conceptions about the nature and practice of engineering.

The potential problem lies not in using engineering design to learn science concepts per se, but in the epistemic stance about engineering knowledge and goals represented in classroom design activities. If we are to realize the goal of technology literacy for all students, simulated engineering design activities in the classroom must be based on an epistemology of authentic engineering design practice. My question is whether and in what ways engineering design activities used for the purpose of teaching science concepts reflect an epistemology of real-world engineering practice.

In this paper I will explore the implications of an epistemology of authentic engineering design for design activities in the secondary science classroom, following Chinn & Malhotra's (1999) analysis of the epistemology of authentic versus classroom science experimentation activities. Because an epistemology of engineering design hasn't been well-specified yet, the main work of this paper is to develop elements of it.

I begin in the first section by identifying the impetus for technology education generally, and engineering design specifically, in the education standards. In the following section, I overview examples of curricula employing engineering design activities in secondary science classrooms that have been reported in the educational research literature and consider them with regard to perspectives on education for technology literacy. I then present a socio-cultural justification for the alignment of classroom engineering design activities with authentic engineering design, particularly with regard to their epistemic elements. Next, I devote most of my effort to deriving an epistemology of engineering design from philosophy and sociology of engineering writings. I conclude by considering how an engineering design epistemology can be more fully considered in classroom design activities to further technology literacy and identifying areas in which further research is needed.

The Call for Technology Literacy

> *As long as there have been people, there has been technology. Indeed, the techniques of shaping tools are taken as the chief evidence of the beginning of human culture. On the whole, technology has been a powerful force in the development of civilization, all the more so as its link with science has been forged. Technology ... is an intrinsic part of a cultural system and it both shapes and reflects the system's value* (Rutherford & Ahlgren, 1990, chap. 3, p. 1).

Technology is part of our cultural past, present, and future. We live in a world characterized by increasingly complex technologies. People encounter technology through the products they use every day, for example, telephones, appliances, furniture, clothing, utensils, vehicles, and toys. Virtually every career field involves some relationship with technology, too, from simply using technologies such as computers or cash registers to engaging in technology-based endeavors such as engineering or manufacturing. Technology issues are ever present in social, political, and cultural realms as well, for example, issues of technological causes of global warming and the moral and ethical dimensions of cloning humans.

In the United States, national, state, and local K-12 education standards assert the need to prepare *all* students to live and work in a technological world—to achieve *technological literacy* (Rutherford & Ahlgren, 1990; NRC, 1996; ITEA, 1999; WDPI, 1998; MMSD, 2001). The standards consider technologically literate students to be prepared for competent practice in a technologically oriented society, whether in continued education for a technology-based profession, participation in a job that relies on technology (most all jobs), individual consumerism, or decision-making about environmental or societal implications of technology. Specifically, the standards define technology literacy as both knowledge and skills, as understanding 1) the nature of technology – its characteristics and scope and the interrelationships between technology, science, and mathematics, 2) social and environmental issues in technology, 3) attributes of design and engineering design, 4) the designed world – medical, industrial, communications, etc., and 5) having the ability to apply the design process and assess the impact of products and systems.

Involving students in design activities is a thread that runs through the standards as a way to lay a foundation for students' technology literacy (AAAS, 1993; NRC, 1996). The standards set the goal for middle- and high-school students to go beyond *understanding* design to develop design *capability*, "that combination of ability and motivation that transcends understanding and enables creative development" (Kimbell, Stables, & Green, 1996, p. 25). Students develop capability through opportunities to engage in solving technological problems (Harding & Rennie, 1993) and to reflect on the problem, process, and solution.

Definitions

Before progressing further, I define what I mean by the key terms of *technology*, *engineering*, and *design* in the conversation of technology literacy.

Technology.

Technology as broadly construed refers to "the made world." It is defined in contrast to *science*, which is concerned with "the natural world." Technology refers both to an activity – "how people modify the natural world to suit their own purposes" (ITEA, 2000, p. 2), and to the outcomes of the activity – objects contrived for a useful purpose, i.e., scientific implements, toys, weapons, art, systems, and environments (Gilbert, 1992, p. 566). Specific examples of technological outcomes include "the

Aswan High Dam, the contraceptive pill, steam engines, pesticides, public-opinion polling, [and] penicillin" (AAAS, 1993, Ch. 3).

Engineering. Some conceptions of *engineering* perceive it to be indistinguishable from *technology* and use the terms interchangeably (Sparkes, 1993b). However, I take engineering to be a specific type of technological activity. Education standards describe *engineering* as "the component of technology most closely allied to scientific inquiry and to mathematical modeling" (Rutherford & Ahlgren, 1990, p. 2). I devote space in a later section to examine its characteristics in more detail. For now, the activity of engineering may be generally described as construing a problem and creating a technological solution to it. Familiar domains of engineering include electrical, mechanical, civil, chemical, and structural engineering. Engineering a solution to a problem requires using scientific knowledge, engineering knowledge, properties of materials, and construction techniques and factoring in issues of cost, safety, appearance, environmental impact, and effects of failure (AAAS, 1993).

Design. Engineers, among other professionals, engage in the activity of *design* to devise artifacts in response to criteria and constraints (Rutherford & Ahlgren, 1990). *Criteria* are the specifications a design must meet; *constraints*, the boundaries within which the design must fit. Like the term *technology*, *design* refers to both an activity and the outcome of the activity, which may take the form of drawing, model, prototype, or specifications for implementation. In essence, designs as products are "blueprints" for creating artifacts.

Design is considered "an integral part of the engineering process and indeed, … its central philosophy" (Lewin, 1986, p. 11). Schön (1983) notes that some social scientists tend to think about anything created as products of design, for example, manufactured products, business management systems, and architecture (Simon, 1969), clothing and graphic art (Hill & Anning, 2001) or to think about *all* knowledge as designed (Perkins, 1986). While at some level of abstraction, it can be said that design is the same everywhere (Bucciarelli, 1994), Schön questions how far to take this view, because in doing so we “risk ignoring or underestimating significant differences in media, contexts, goals, and bodies of knowledge specific to the [different] professions” (p. 77). Indeed, cognitive theory reminds us that expertise is domain-specific. Therefore, I focus my discussion on *engineering design* as it best describes the technology activities arising in secondary school science classrooms.

In the next section I survey curricular approaches that include the technological activity of engineering design and factors influencing the approaches taken.

Approaches to Engineering Design in the Science Classroom

Until recently, technology education in secondary schools was the domain of elective, skills-based industrial arts and vocational programs. The academic standards published over the past decade, however, emphasize a broader technology education for *all* students. Now the American Association for the Advancement of Science (AAAS) identifies technology education as one of the three major areas of science education, along with mathematics and science itself (Rutherford & Ahlgren, 1990). Technology education may enter secondary schools in a variety of ways, but the examples in the educational research literature tend toward incorporating design activities in the science classroom for the purpose of learning science concepts and practices. I review examples of this approach, describe an alternative model of using design activities for the purpose of learning technology concepts and practices, and then discuss factors that influence the approach taken to design in the science curriculum.

Design as a Means for Science Education

A review of the educational research literature yielded only a few examples of secondary school curricula in the United States that include elements of technology education generally, or engineering design education specifically. Other countries, especially European and United Kingdom (England, Wales, Scotland, and N. Ireland) and Commonwealth countries (e.g., Australia and Canada), have more extensive and mature technology education programs than the U.S. However, because conceptions of the purpose and form of technology education differ between countries (Black, 1998), I limit my review to U.S. school curricula.

The curricula I identified take science learning as their primary goal – engineering design is used to provide a real-world context for science. The curricula developers posit students' desire to improve their designs will provide an impetus for learning the science. Differences between science and engineering design are largely glossed over in discussion of these curricula, with the tendency to refer to both generically as *science*, and the discussion takes place in the language of science rather than engineering.

Engineering competitions. Sadler, Coyle, and Schwartz (2000) employ engineering design challenges in middle-school science classrooms as opportunities "for students to acquire science process skills and learn physical science concepts" (p. 300). They find design projects desirable because they help show "the connections between science concepts and solutions to real-world problems. Making the right connections should result in better [design] solutions" (p. 303). Examples of their design challenges include making a paper bridge truss of the least weight to support a given load and optimizing an electromagnet to lift the longest chain possible.

Learning by Design™ (LBD). Kolodner and her research group (Kolodner, 2002; Holbrook, et al., 2001) developed the LBD™ curriculum to "help middle school students … learn science content such that they can apply it in new situations and to engage skillfully in the practices of scientists … in the context of engaging in design challenges" (Kolodner, 2002, p. 2). The design challenge provides the reason for learning the science content. The developers refer to the curriculum as "inquiry science." The LBD™ set of curricula include designing, building, and testing a balloon-powered miniature vehicle to travel a given distance over a specified terrain and designing a solution to keep the dirt on a model hill from accumulating on a basketball court at its base. An earlier LBD curriculum employed designing and modeling of systems as a way to “help children acquire a deeper, more systematic understanding of such complex domains [as natural and physical science]” (Hmelo, Holton, & Kolodner, 2000, p. 247).

Design-Based Science (DBS). DBS, developed by a team at University of Michigan (Fortus, et al., 2002; Mamlok, et al., 2002), “aims to help [high-school] students construct new scientific understanding and real-world problem-solving skills … in the context of designing artifacts” (Fortus, et al., 2002, p. 3). The developers consider DBS to be a particular type of inquiry-based science curriculum. Examples of DBS curricula including designing and building a model house that can withstand extreme environmental conditions and designing and building a wet cell battery that makes use of nontoxic materials.

Design, technology, & science. Seiler, Tobin, and Sokolic (2001) introduced an engineering design activity in an urban high school “to enhance the student’s understanding of Newton’s laws and the equations of motion” (p. 751) – that is, their understanding of science concepts. The authors take the view “that science and technology are deeply integrated fields” and they “see no merit in considering scientific knowledge as separate from the technological artifacts associated with its production” (p. 748). Students undertaking this curriculum were challenged to design, build, and race miniature cars powered by balloons.

Design as a Means for Technology Education

An alternative to the conception exemplified by these curricula is one that considers the purpose of technological activities such as design in the classroom to be for learning *technology* concepts and practices. This view acknowledges there’s a lot to be gained in making connections between science and technology. But it holds that "science and design & technology are so significantly different from one another that to … [ignore it] is both illogical and highly dangerous to the education of pupils" (Barlex & Pitt, 2000, p. 7). To ignore their differences is considered antithetical to developing technology literacy because such an approach presents a distorted view of the nature of design & technology.

This conception takes technology concepts and practices themselves, including design, to be subjects of learning in a context that draws on multiple disciplines of mathematics, language arts, and social studies in addition to science. An example of this perspective can be found at the early middle-school level (Grade 6) in the City Technology project (Benenson, 2001). Subjects of the City Technology curricula include technologies of mapping; environmental analysis & design; mechanisms, circuits and controls; packaging and structures; and signs, symbols and codes.

Factors Influencing Curricular Approaches

As products of instructional *design* (Perkins, 1986), curricula are subject to the values and beliefs of their designers (Schön, 1983) as well as the criteria and constraints of their environment (Rutherford & Ahlgren, 1990). Factors influencing how engineering design is incorporated into the science classroom include curriculum developers' and teachers' views of the relationship between science and technology, their beliefs about the form technology education should take, and constraints and criteria of the classroom.

View of relationship between science and technology. Ultimately, "the nature of the perceived relation between science and technology [or engineering] will govern the relation between science education and technology education" (Lewis, as cited in Gilbert, 1992, p. 564). Gardner (as cited in Barlex & Pitt, 2000) describes multiple views of this relationship: *technology as applied science view* in which science drives technology; *demarcationist view* that science and technology are strictly independent; *materials view* that technology drives science; and *interactionist view* in which science and technology are distinct but are "in a dialectical relationship, with each informing and being challenged by the other" (Barlex & Pitt, 2000, p. 16). Contemporary thinkers and researchers in philosophy and sociology of technology and engineering espouse an *interactionist* view. In contrast, research into teachers' and students' conceptions about the nature of engineering design reveal a predominant view of *engineering as applied science* (AAAS, 1993; NRC 1996; Lewis, 1992). Different views will manifest in different positionings of engineering design in the science classroom. Those with an interactionist view would likely distinguish between engineering and science goals and means, while those who view engineering as applied science would be more likely to treat engineering primarily as a means for illustrating the applications of science.

Conceptions of technology education. Gilbert (1992) identifies different forms technology education can take that derive from different views about the nature of technology and that reflect different beliefs about its purpose. They comprise education *for*, *about*, or *in* technology. Gilbert relates each form to Pacey's concept of "technology-practice," an operational model that portrays technology practice as having "three, simultaneously operational elements: the technical aspect, the organizational aspect, and the cultural aspect" (p. 565).

Gilbert describes an approach that emphasizes only the technical aspect of technology as "education *for* technology," whose goal is to prepare the student "for work in an overtly technological industry" (p. 568); i.e., to be technicians or engineers. The technical aspect comprises the *products* of technological activities and the *processes* by which they are produced, but neglects consideration of the role human values and goals have in technology production. Education *for* technology allows for exploring the relationship between science and technology and is the primary form technology education takes when incorporated into science class. The *design* process receives heavy emphasis under this form.

Gilbert terms an alternate approach, which emphasizes Pacey's organizational and cultural aspects but neglects the technical aspect, "education *about* technology." Under this form of technology education, "the student would learn how technology is organized and about its consequences, yet would be unable to actually do any technology" (p. 568). Education *about* technology would likely fall under the province of social studies, not science, in schools.

Gilbert considers the most complete form of technology education to be "education *in* technology," which accords all aspects of Pacey's model of technology-practice equal importance. The intention of education *in* technology would be "to provide initial preparation to be a citizen practising [sic] as a technologist" (p. 568). Under this form, technology education would attend to the science, the society, and the technology elements all. This is the most complete but challenging form as it includes both the other forms of technology education. Current education standards reflect this perspective with the attention they give to science-technology-society (STS) topics.

On the surface, engineering design activities in science classrooms may appear to fit the form of "education *for* technology." However, they actually may not fit any of these conceptions of technology education as their motivation is science, not technology education. The curricula I reviewed don't have technology education as their goal —they are using *design* primarily as a vehicle to scaffold science learning and to support such general education goals as decision-making and working in teams.

<u>Influences of classroom culture.</u> The role of engineering design activities in the science classroom is shaped by multiple factors, two of which are content goals and disciplinary background.

Science classes still have the science-specific parts of education standards to meet and teachers and curriculum developers must consider what's worth teaching with their finite resources (Lehrer & Schauble, 1999). Engineering as a practical field is generally not afforded the same status as is science as an academic field (Simon, 1969). In the eyes of teachers and curriculum developers, design activities may primarily provide an option for motivational, "hands-on" learning of abstract science concepts through their concrete technological instantiations.

Traditional disciplinary boundaries in middle and high schools don't provide a clear home for today's conception of technology education. Technology topics are interdisciplinary, spanning at a minimum, industrial arts and science, but ranging further to social studies, communication, and mathematics. A teacher's (or curriculum developer's) disciplinary background plays a determining role in how technology topics are treated—science teachers tend to emphasize abstract science concepts; industrial arts teachers, skills and realized technologies (Barak & Pearlman-Avnion, 1999; Hepburn & Gaskell, 1998; Jones, 2001).

Conclusion

How technology education is implemented in schools can vary significantly based on the underpinning philosophy of technology and how the purpose of technology education is conceived (Black, 1998; Gilbert, 1992; Ropohl, 1997) in addition to classroom constraints and criteria. By using design activities in the science classroom to scaffold *science* learning, we end up with a hybrid that "represents an uneasy compromise between the wish to establish a new discipline [of technology] and a concern to disseminate more widely aspects of selected practical activities [of design]" (Gilbert, 1992, p. 572). With this hybrid, we may be in danger of creating a new, classroom-unique culture that doesn't resemble real-world engineering design practice and thus may present a distorted view of the nature of technology. To avoid the risk of classrooms becoming self-contained cultures, we need to consider how we can align them with real-world practices (Wenger, 1998).

Theoretical Basis for Aligning Classroom with Professional Practice

The education standards call for educators to model curricula more closely on technology as carried out by real-world practitioners. Situated cognition theory provides a productive starting point for thinking about alignment of classroom and professional practice with its focus on "learning as participation in social practice." Underlying the situated perspective is a view of "the inseparable duality of the social and the individual" (Wenger, 1998, p. 4). Vygotsky (1978) leads us to consider individual cognition as it arises from social practice. Both situative and cognitive theories can be useful in thinking about alignment of classroom and real-world practice as they "cast light on different aspects of the educational process" (Anderson et al., 2000, p. 11).

In this section I provide a theoretical basis for aligning classroom with professional practice, beginning with elements of situative theory most relevant to the issue of "alignment," moving on to considering the classroom as a community in sociocultural terms, and then to individual cognition, specifically epistemology, as it arises from social practice.

Situative Concepts that Support Alignment

Situative, or situated cognition, theory is an umbrella term for sociocultural perspectives that view knowledge as "a product of the activity and situations in which … [it's] produced" (Brown, Collins, & Duguid, 1989, p. 33). Situative theory is partially a reaction to the limited place for culture, context, and activity in cognitive theory (Cobb & Bowers, 1999). Situated theorists challenged the cognitive perspective that separated *what* is learned from *how* it is learned and used, arguing that current research supports a different perspective of learning:

> The activity in which knowledge is developed and deployed … is not separable from or ancillary to learning and cognition. Nor is it neutral. Rather, it is an integral part of what is learned. Situations might be said to co-produce knowledge through activity. Learning and cognition … are fundamentally situated. (Brown, Collins, & Duguid, 1989, p. 32)

Situative concepts give us a framework for thinking about classrooms' alignment with professional practice. Relevant concepts include: community of practice, knowledge-in-use, competence, trajectory of participation, and enculturation.

Wenger (1998) defines learning as social participation – as individuals "being active participants in the *practices* of social communities" (p. 4). Participation in a community's practices is *doing* "in a historical and social context that gives structure and meaning to what we … practice" (Wenger, 1998, p. 47). The idea of community of practice emphasizes knowledge as *knowledge-in-use* (Riel & Polin, 2001). Situated theory "promotes a view of knowing as activity" (Lave & Wenger, 1991, p. 52) by participants within an organizational context. Knowing and doing are intertwined and inseparable (Brown, Collins & Duguid, 1989).

Wenger (1998) asserts knowing is "what would be recognized as competent participation in the practice" (p. 137). *Competent practice* includes the ability to connect with other members in the practice, to understand and take responsibility for the pursuits of the practice, and to engage in the repertoire of the practice. The community itself determines what it means to be a competent participant in its practice.

Learning is "synonymous with changes in the ways that an individual participates in social practices" (Cobb & Bowers, 1999, p. 6). To acquire the conceptual tools of a practitioner in a community, a beginner must "enter that community and its culture" (Brown, Collins & Duguid, 1989, p. 33). *Enculturation* is a process of adopting the belief systems and practices of a community. Lave & Wenger's (1991) concept of "legitimate peripheral participation" conceives of participants moving along a *trajectory of participation* from naïve to novice to expertise.

Situative theory's implications for education are that we consider students as novices on a trajectory of increasingly central participation in a real-world community of practice; that we take a view of knowledge as practice; and that we consider the target community of participation to be real-world engineering design. The community in which we should enculturate students is the community of engineering design as it exists beyond the classroom.

Classrooms as Communities

However, classrooms can't be totally aligned with professional practice because of important differences between these communities – in their organizational contexts; goals; resources of materials, time, and expertise; and scope and reach of their outcomes and products. However, to place the classroom experience on a trajectory of increasing participation in real-world practice, some degree of alignment of communities is necessary.

For students to apply what they have learned in the classroom to the real-world they must move from one practice to another (Wenger, 1998). Building links to real-world practices outside the classroom can help to place the classroom experience on a trajectory of increasing participation in real-world practice. Wenger (1998) identifies one kind of link between communities to be *boundary objects*— processes, concepts, terms, and artifacts, for example, that belong to both professional and classroom practices. Wenger recommends appropriating styles and discourses of the profession in which one expects to participate as another link that can ease the transition. Links may be established also through *brokering* “provided by people who can introduce elements of one practice into another” (Wenger, 1998, p. 105). Curriculum developers and teachers may be considered potential brokers.

Hay & Barab (2001) describe a *simulation model* for classrooms that makes use of linking. Under the simulation model “the classroom environment (both in terms of goals, practices, instruments, and peer relationships) should be made as similar to communities of practice outside of the school as possible” (p. 313) to assist in facilitating this transition. Students learn within temporarily formed groups of peers referred to as *activity groups*. Activity groups don’t fully qualify as Wenger’s (1998) communities of practice, in that they’re not part of an activity system in which participants have a significant history and future in the practice or a way to sustain itself and evolve through future generations. Riel & Polin (2001) use the term *micro-communities* for such task-based classroom communities that end with the production of a common learning product.

Their status as true communities notwithstanding, activity groups or micro-communities can achieve aspects of authentic practice by participating in practices commensurate with those of the “real world” domain and by the realism of their outcomes with regard to real-world issues and users (Hay & Barab, 2001). Shaffer & Resnick (1999) share a similar view of authentic activity as that “connected to important and interesting aspects of the world beyond the classroom, [and] grounded in a systematic approach to thinking about problems and issues" (p. 203)[1].

Individual Epistemology Developed in Social Practice

The norms and practices of communities of practice shape the ways of thinking and belief systems of its members (Brown, Collins & Duguid, 1989; Cobb & Bowers, 1999; Hogan & Maglienti, 2001). Vygotsky (1978) theorized that cultural activity occurring on the social plane becomes internalized as higher-order cognitive tools of individuals, including, for example, their epistemic cognitive processes (Kitchener, 1983. Hogan and Maglienti (2001) provide evidence that scientists develop their epistemologies "through becoming active contributing members to their communities of practice" (p. 684), epistemologies which they internalized as personal knowledge that guided their actions and interactions with members of their communities.

Webster's dictionary defines *epistemology* as the study or theory of the origin, nature, methods, and limits of knowledge (Guralnik, 1980). The epistemology of a domain is commonly referred to as "the nature of" science, technology, or engineering, for example (Jones, 2001; De Vries & Tamir, 1997; Rudolph, 2002). Epistemological knowledge of a domain includes knowledge about the limits of knowing, the certainty of knowing, and the criteria of knowing (Kitchener, 1983). The understandings and beliefs

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[1] My presentation of Hay & Barab's (2001) and Shaffer & Resnick's (1999) conceptions of authenticity in education is incomplete. They both also include, for example, the criteria that activities be personally meaningful to students, an important point for Buxton (2002) as well. Additionally, Shaffer & Resnick include the element of instructional validity in assessment as a component of their concept of *thick authenticity*. These are important considerations, but because my focus is on alignment with professional practice as an element of authenticity, I will not address these other components in this paper.

one holds about the nature of a domain affects how one reasons about problems and what s/he identifies as appropriate solutions.

Situative researchers hold that different forms of reasoning develop from different practices involving different artifacts and organized by different motives (Brown, Collins, & Duiguid, 1989; Cobb & Bowers, 1999). Beach found the commensurability of mathematical reasoning in and out of the classroom is a function of the strength of the relationship between <u>learning environment</u> participation and <u>social activity</u> participation (as cited in Cobb & Bowers, 1999). Therefore, students should be enculturated into epistemological reasoning in a domain and in using it in ways that might be judged appropriate by more experienced members of the relevant community (Leach, Millar, Ryder, & Sere, 2000).

Chinn & Malhotra (1999) examined the alignment of classroom science experiments with those in real-world science laboratories with regard to their underlying cognitive models. Differences in cognitive models lead to different cognitive processes being used in reasoning about simulated classroom versus authentic real-world experiments. They argue if classroom tasks are not aligned with real-world tasks along dimensions of their underlying cognitive models, the cognitive reasoning processes needed, and epistemological assumptions, students will learn something other than science as it's recognized by real world practitioners. This situation would not contribute to enculturation and could in fact be detrimental to literacy because students, by participating in non-aligned science (or engineering) practices in the classroom, would likely develop an epistemology at odds with that of practicing scientists (or engineers), jeopardizing their ability to participate in that culture.

Conclusion

Situative theory lead us to think about classroom design activities in terms of their *alignment* with professional engineering design activities. If learning is a process of enculturation into a community of practice, then to learn engineering design one must begin by participating in the engineering design community's practices, using the domain's cultural tools in authentic activity (Brown, Collins, & Duguid, 1989). The epistemology of a domain, or its belief system, must be "instilled in the only way it can be, through practice in which the students actively take part" (Brown, Collins, & Duguid, 1989, p. 38). Thus we must attend to the epistemology of engineering design underlying classroom design activities.

I will take an epistemological lens (Martin, Kass, & Brouwer, 1990) to consider the alignment of classroom with professional engineering design. I first turn to the task of deriving elements of the epistemology of engineering design, drawing from research in the philosophy and sociology of engineering design.

Toward an Epistemology of Engineering Design

Just as we now understand there is not just *one* science (Buxton, 2001; Knorr Cetina, 1999; Rudolph, 2002), we also acknowledge there is not just *one* engineering (Jones, 2001; Schön, 1983). In her study of science practice, Knorr Cetina (1999) emphasizes the disunity of the sciences, noting differences in how scientific knowledge is practiced within different structures, processes, and environments that comprise different epistemic cultures. Schön (1983) describes similar differences between subcultures and indeed, between practitioners, of engineering design. Bucciarelli (1994) notes fundamental ingredients in the engineering design process are "the norms and practices of the subculture of the firm" (p. 23) in which the design takes place. The epistemic culture of engineering design is situated in its local context—the setting of a particular firm or organization, the schooled background and expertise of participants, and the appreciative systems and role frames participants bring to the task.

Still, there are elements in common across engineering design practice that characterize it as a culture. It's to this level I turn to sketch an epistemology of engineering design practice—in short, to describe the kind of knowing in which competent design engineers engage (Schön, 1983). De Vries & Tamir (1997) point out that while the epistemology of technology and engineering design has been receiving attention recently, "[it] is by no means yet a fully developed area" (p. 7). My goal is not to develop a conclusive epistemology, but to raise aspects of the epistemic culture of engineering design to which we must attend in education if we are concerned about developing technological literacy.

I draw on philosophy and sociology accounts of engineering design to identify elements of the nature of engineering design. The following epistemic elements are revealed by these accounts as central to the practice of engineering design: objectives and objects; relationship between science and engineering; design as situated, emergent, and reflective; designing solutions under criteria and constraints; design as activity; design as social process; and conceptual knowledge in design.

Objectives and Objects of Engineering Design

It is informative to first draw an important, fundamental distinction between the goals and the natures of reality investigated by engineering design and scientific inquiry. The goal of *engineering design* is the creation of artifacts that meet human needs or wants; in contrast, the goal of *science inquiry* is to develop knowledge and understanding of natural phenomena (Sparkes, 1993b; Rutherford & Ahlgren, 1990; NRC, 1996). Engineering design investigates natural effects just as far as they support the device or object under design (Ropohl, 1997). The primary goal of engineering design is not to create knowledge, but to devise solutions to problems, although knowledge is created in the course of designing. With their different goal orientations and realities investigated come different beliefs and theories about the nature and limits of knowledge and its acquisition, norms for accepting assertions, and ways the social is made to work – different epistemic cultures.

Engineering's Relationship to Science

The nature of science's relationship to engineering is fundamental to understanding of and education in engineering practice. Schön (1983) rejects the philosophy of technical rationality that sees engineering design as simply "the application of scientific theory and technique to the instrumental problems of practice" (p. 30). He argues technical rationality neglects an important aspect of engineering design practice—situations emerge throughout the course of practice that may require the designing engineer to reframe her/his understanding of the problem in response:

> When the phenomenon at hand eludes the ordinary categories of knowledge-in-practice, presenting itself as unique or unstable, the practitioner may surface and criticize his initial understanding of the phenomenon, construct a new description of it, and test the new description by an on-the-spot experiment (p. 62).

This problem-*setting*, the "process by which [one defines] the decision to be made, the ends to be achieved, the means that may be chosen" (p. 40), is a necessary condition for problem-*solving*, but is not itself a technical problem to which scientific theory and technique may be applied. Schön acknowledges designing engineers do make use of scientific knowledge to solve problems, but "large zones of practice present problematic situations which do not lend themselves to applied science" (p. 308). Bucciarelli (1994) concurs with Schön's view, pointing out technical rationality, or science determinism, "misses the complexities of alternative forms and paths to a design, … it ignores the diverse interests of participants in the design process, … and it fails to acknowledge the indeterminacy of technical constraints and specifications and … their negotiation in process" (p. 185). The consensus is that "applied science" is an inadequate view for the nature of engineering design, and furthermore, that an interactionist view is more appropriate (Barlex & Pitt, 2000).

Engineering and scientific projects are usually not "pure" science or engineering, but incorporate elements of each (Roth, 2001a). While *people* may engage in both activities, the *activities* in which they engage remain either science or engineering

(Sparkes, 1993b). I'll return to this topic in discussing how experimentation is used for both inquiry and design ends, under the section on "design as activity."

Rather than one determining the course of the other, engineering and science support each other—engineering endeavors sometimes yield scientific discoveries, and scientific explanations sometimes present new technological possibilities; science contributes understandings of natural phenomena to engineering, engineering contributes instruments by which scientific investigations may be carried out (Schön, 1983; AAAS, 1993).

Design as Situated, Emergent, Reflective Practice

Social scientists have come to view knowledge as practiced (Pickering, 1992; Knorr Cetina, 1999), compatible with the situative view of knowledge. Not only does situative theory provide us a way to think about developing technological literacy, it also provides a theoretical framework for describing engineering design activities. McCormick (1997) finds "evidence in accounts of design, that parallels the findings of those who take a situated cognition perspective; namely that objects, tools, solutions and problems all interact to determine design thinking" (p. 151). Roth (2001b) provides evidence for the situated nature of design processes, concluding they "cannot be modeled solely as mental processes, but include material, social, and historical elements" (p. 213). Bucciarelli (1994) also notes the situativity of design—"the singular shows its own quirks and special features and demands tailoring of generic knowledge, no matter how sophisticated or detailed, to fit the special circumstances of the immediate design task" (p. 77).

Engineering design requires a flexible response to the circumstances of the design task. Schön (1983) characterizes engineering design as “reflective conversations with the materials of a situation” (p. 172). He describes reflection-in-action as a way that designing engineers cope with the situations of their practice characterized by complexity, uncertainty, instability, uniqueness, and value-conflict (p. 39). Pickering (1995) portrays engineering design as a “dance of human and material agency” that takes the form of a “dialectic of resistance and accommodation” (p. 22). A phenomenon *resists* capture by the designing engineer, requiring him/her to take action to *accommodate* the phenomenon. The engineer asserts her/his goals, taking a stab at understanding or manipulating a phenomenon, “trying first *this* material configuration…, then *that* interpretive account, and so on” (p. 91). Bucciarelli (1994) echoes the idea of emergence, observing that in design, “the mind poses an explanation; the object is poked and responds” (p. 70).

To summarize, social scientists have converged on a description of engineering design practice as situated in the circumstances of the immediate design task, characterized by generation and resolution of dilemmas in an emergent, reflective dialogue with the materials of the situation.

Designing Solutions under Criteria and Constraints

The specifications for a design include the constraints and criteria it is expected to meet. As discussed earlier, criteria form the operational goals for a design; constraints, the operational boundaries. Constraints are actually as necessary for design as they are limiting; without constraints, the outlines of the object to be designed would be indiscernible (Bucciarelli, 1994). Constraints may be absolute, such as physical laws or physical properties that impose limits on a design; other constraints may be somewhat flexible, for example, financial, regulatory, social, environmental, ethical, and aesthetic (Rutherford & Ahlgren, 1990). Like all other elements of design, specifications are subject to interpretation and negotiation in the process of designing (Bucciarelli, 1994; Pickering, 1995).

It's not always possible to satisfy all constraints and criteria, and trade-offs between them are required—a decision-making act that takes into account personal and social values in addition to values of the subculture, the local context of designing, as well as values of the customers or users. It follows that there is no "perfect" design and that alternatives are possible. Simon (1969) introduced the term *satisficing* to refer to "decision methods that look for good or satisfactory solutions instead of optimal ones," arguing that "in the real world we usually do not have a choice between satisfactory and optimal solutions, for we only rarely have a method of finding the optimum" (p. 138). Because designs aren't perfect, they have unintended side effects and are subject to failure, making risk analysis an important concept in designing a solution.

Design as Activity

Design process models that indicate steps, even if they are seen to be iterative and cyclic, don't tend to represent what engineering designers do in practice. Ideas of feedback and iteration rest on the assumption of a temporally ordered process. As described earlier, engineering designers' approach to design is flexible and in response to the materials of the situation. Standard design process diagrams belie the complexity, uncertainty, ambiguity, unpredictability, creativity, and variability of designing.

(Bucciarelli, 1994). Bucciarelli holds “a less neat vision of technology is required” (p. 48) than is traditionally presented.

Thus, instead of laying out a process model, I’ll describe activities in which designing engineers partake as they go about their work. Buciarelli (1994) observed engineers across several contexts “applying the fundamental concepts and principles of their disciplines, manipulating hardware, analyzing, sketching, instrumenting, testing, modeling, and constructing scenarios describing the way things work, or ought to work, in their struggle to gain mastery over their designs” (p. 76). I will examine the nature of several of these activities more closely: using disciplinary knowledge, modeling, experimenting, and constructing scenarios. Of course, this is not the complete set of designing activities – they also include cost estimation; risk analysis; quality assurance; project planning; presenting; interacting with implementers, purchasers, marketers; etc., but these are central to and characteristic of designing in an engineering context.

Applying disciplinary knowledge. Engineers rely on their understanding of the principles and concepts of their discipline, for example, mechanics, chemistry, or electrics, to make their designs. Scientific principles, such as the law of conservation of energy or properties of surface chemistry, provide engineers with understandings of the behavior of objects. Scientific and mathematic principles may provide the underlying form and basis for an engineer’s work or they may be drawn on to understand and solve emergent design problems. Bucciarelli (1994) notes at times, designing engineers “see” objects in terms of *abstract*, often idealized, scientific and mathematical concepts and relationships; for example, stresses and strains, circuit relationships, energy flow, or momentum. At other times, designing engineers talk about *concrete* materials of the situation; for example, the performance of a particular photovoltaic module. Designing engineers also require an intermediary form of knowledge between scientific mathematic abstraction and specific device knowledge (Gilbert, 1992; McCormick, 1997) referred to as *technological laws* (Ropohl, 1997), which I will discuss further in the section on conceptual knowledge.

Design engineers use their scientific, mathematics, and technological knowledge in *modeling* and *experimentation* of the same kind used in scientific inquiry, albeit with important differences in their qualities and purpose. The methods provide engineers with a means of determining a system's or object' functional and behavior characteristics, of predicting behavior, and testing and evaluating designs (Lewin, 1986; Rutherford & Ahlgren, 1990; Sparkes, 1993b). I next consider each method in its engineering context in more detail.

Modeling. Abstract and reductionist "models of the sort prevalent in science … are essential to the work of designing engineers" (Bucciarelli, 1994, p. 84). Scientific models provide designing engineers a reliable source of information on which to base their designs (Sparkes, 1993a). Engineering models are representations that capture behavior of objects and "reveal that behavior in hard causal and quantitative terms" (Bucciarelli, 1994, p. 67). Engineering models derived from basic science concepts need not *explain* the natural phenomena underlying an object's behavior as in science, but they need to represent the object or system accurately enough to explain and predict its *behavior*. Science concepts are oftentimes necessary but not sufficient for engineering models, which must also take into account the concrete materials of the situation—such as the environment of operation, particular materials, tolerances and limits, and interfaces with other objects or systems (Sparkes, 1993a). A key difference in modeling between science and engineering design is that "science investigates extant forms; design initiates novel forms" (Cross et al., 1986, p. 19). Models may be mathematical, physical, conceptual, computational, or in the form of drawings and sketches.

Experimenting. The use of experiment figures prominently in both science and engineering design. AAAS (1993) describes the roles associated with experiments in science and engineering. In science, experiments are used to understand the relation between causes and effects, to show that theories fit the data, or to discover something. In engineering design, experiments are used to produce a desirable outcome, as feasibility tests to demonstrate that designs work and reliably so, or to cause something to happen.

In engineering design, participants employ experiments in both scientific and engineering roles, as revealed by the following example of developing a process for bluing gunmetal. In this example, Schön (1983) provides a picture of designing as interweaving engineering design and scientific discovery through stages of diagnosis, experiment, pilot process and production design.

> At each stage of this process, the students were confronted with puzzles and problems that did not fit their known categories, yet they had a sense of the kinds of theories (surface chemistry, thermodynamics) that might explain these phenomena. They used their theoretical hunches to guide experiment, and on several occasions their moves led to puzzling outcomes—a process that worked, a stubborn defect—on which they then reflected. Each such reflection gave rise to new experiments and to new phenomena, troublesome or desirable, which led to further reflection and experiment (p. 176).

As shown in this example, experiment may be aimed both at testing a particular hypothesis (i.e., scientific inquiry) and at achieving a particular technological effect (i.e., engineering design). Figure 1 illustrates the use of experiment in design to investigate phenomena or to affirm or negate design moves, in a process that interweaves the activities of science and engineering.

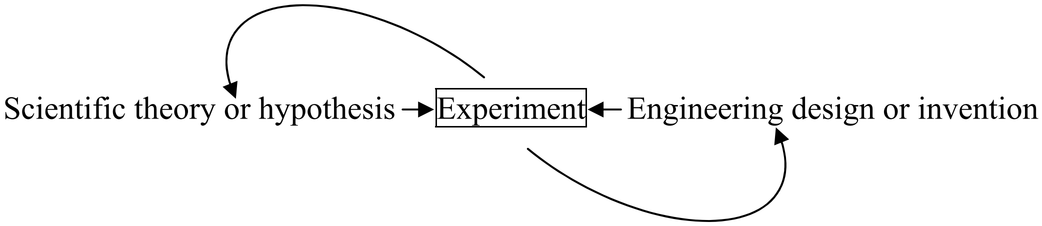

Figure 1. Use of experiment in engineering design.

Although experiment is used for both scientific inquiry and engineering design, it takes different forms depending on its purpose. Schauble, Klopfer, & Raghavan (1991) found the ends affected the means in experimentation—student experimenters holding a science goal of understanding a phenomenon conducted qualitatively different experiments than those who held an engineering goal of causing something to happen. Their research showed a relationship between the purpose and the processes of experimentation.

A particular way experimentation is used within engineering design is *testing* feasibility of designs and performance of alternatives (Bucciarelli, 1994; Lewin, 1986). There is much testing intent on falsifying designs; concepts of measurement and fair test are important in establishing viability of designs. Feasibility testing is a complex affair as there are often too many dimensions and variables to allow a comprehensive "control of variables" experimentation strategy. "The isolation of causes and effects, with one parameter driving another, … [may be] impossible given the resources [at an engineer's disposal]" (Bucciarelli, 1994, p. 74). Furthermore, objects usually have to function in uncontrolled environments, making it "impossible to carry out all the tests, to develop and pursue all the possible scenarios about the behavior of objects to fully verify a design" (Bucciarelli, 1994, p. 72). Additional complicating factors are unknown characteristics of new object components and the uncertain reliability of instruments.

Constructing scenarios. Bucciarelli (1994) describes the process of designing as constructing scenarios "describing the way things work, or ought to work, in their struggle to gain mastery over their designs" (p. 76). Scenarios are stories about the *object worlds* in which participants work, which comprise the hardware of the artifact, plus the techniques and methods, empirical and personal knowledge, scientific theories and knowledge that together constitute the engineer's understanding of how the device or object under design works (these knowledge elements are discussed further in the section on "conceptual knowledge"). Bucciarelli defines *object-world rhetoric* as the shared common discourse of engineering design. Object-world rhetoric is

> more than a common vocabulary and syntax, it is a web of tacit understandings of what is to be considered an honorable claim, a significant conjecture, a valid 'proof,' or a laughing matter (p. 83).

It is in the terms of this rhetoric that object-world stories are described, proposed, critiqued, accepted, or rejected. Scenarios, or object-world stories, are the media of communication among designers and evaluation of a scenario's quality equates to evaluation of the quality of the design itself. Designers have flexibility in creating object stories, but these aren't fictional accounts. Object world stories are backed up with evidence provided by, for example, computer models, laboratory tests, field data, and prototypes. Designing engineers strive for fixed, repeatable, consistent models of objects or systems. An account is considered complete once all uncertainty and ambiguity are eliminated. A successful design outcome is a conclusion that affirms a story, denies a story, or changes a story; an unsuccessful outcome, a story not able to be written (Bucciarelli, 1994). Of course, the final arbiter of a design's quality is its performance in the operational environment (Ropohl, 1997; L. Schauble, personal communication, March 8, 2002).

Design as Social Construction

Bucciarelli (1994) notes that not only is designing work *within* the object worlds of different participants, it is also the *intersection* of the object worlds of multiple participants. He views design as

> a process of bringing coherence to these [multiple] perspectives and interests, fixing them in the artifact. Participants work to bring their efforts into harmony through negotiation. This harmony, or lack of it will be reflected in the artifact (p. 187).

To communicate, negotiate, and compromise is to design. Agreement and consensus are essential to moving the design forward, but "it does not necessarily follow that all participants share the same vision of the design even when consensus is achieved and even when the artifact has been realized in hardware" (Bucciarelli, 1994, p. 178). The design itself cannot be found in drawings or specifications or even prototypes, "nor is it in the possession of any one individual to describe or completely define" (Bucciarelli, 1994, p. 187). The design exists only in a distributed, social, situated sense (see also Nersessian, et al., 2002; Roth, 2001b).

To achieve quality design, "all participants must be able to explain and describe their experiences [working within their object worlds] to others from different object worlds" (Bucciarelli, 1994, p. 81). The telling, retelling, and hearing of object-world stories are essential to the process of design (Bucciarelli, 1994). In addition to object-world stories, sketches and drawings are also important media of communication in the culture of design engineers. It is a visual culture—"coordination and conflict take place over, on, and through the drawings" (Henderson, 1991, p. 448).

Design always happens in a social context, whether an activity is performed individually or collaboratively in a team. "Clients, customers, venture capitalists, accountants, marketing staff, and competitors may strongly affect the progress and outcome of 'engineering' design" (Benenson, 2001, p. 739). Like all elements of design, the social context is not rigid, but too goes through a life of being shaped, constructed, maintained, and destroyed.

Conceptual Knowledge in Design

While it is true that engineering design is geared toward action, and therefore "know how," it is not true that engineering design is without conceptual knowledge. Engineering design conceptual knowledge includes technological concepts and knowledge specific to the practice of engineering design. Concepts central to the practice of engineering design include systems, control, feedback, trade-off, side-effects, and failure (G. Benenson, personal communication, December 13, 2002; Rutherford & Ahlgren, 1990). I use the rest of this section to describe Ropohl's (1997) categories of technological knowledge in engineering. According to Ropohl, engineering design conceptual knowledge encompasses technological laws, functional rules, structural rules, technical know-how, and socio-technical understanding.

Engineering design requires an intermediate form of knowledge between abstract scientific and mathematical knowledge and specific device knowledge (Gilbert, 1992; McCormick, 1997; Levinson & Murphy, 1997; Schön, 1983). Ropohl's category of *technological laws* refers to such knowledge, that built by adapting natural laws to the real technical process at hand, or by generalizing from empirical results to laws. For example, Hooke's law of elasticity explains the stretch of a material as a linear function of the tension. Adapted to practical technical purposes, the corresponding technological law is: "Whenever the maximum tension effected on a component does not exceed the established percentage of the marginal tension at which Hooke's law ceases to be valid, the component will be wear-resistant" (Ropohl, 1997, p. 68). These laws represent a level of knowledge between the abstract and concrete.

The next type of technological knowledge is *functional rules*, which are specifications of what to do to attain a certain result in certain circumstances, cookbook-style. Expert heuristics (Gigerenzer, 2002), as well as the templates that embodied the knowledge needed to build Gothic cathedrals (Turnbull, 1993), fit into this category. The category of *structural rules* concerns the assembly and interaction of components of a technical system. These rules may be based in scientific knowledge; for example, rules for connecting electrical components derive from Ohm's law. Others, such as rules for reinforcing a framework construction, may originate in historical and current practice. Structural rules are particularly important, as "they support the engineer in creating novel realities, a task which is completely different from scientific research … [and where s/he] has to conceive of a concrete object which does not yet exist" (Ropohl, 1997, p. 69). Structural rules support mental modeling of imagined objects in terms of concrete elements.

The next knowledge type, *technical know-how*, includes tacit and implicit knowledge as well as specific skills of one's practice. This is the knowledge of expertise (Larkin, et al., 1980), built up from thorough practice and experiencing many, many cases

(Rophol, 1997). Schön (1983) refers to this kind of knowledge as "knowing in action" and it includes patterns of action—an engineer's technical repertoire. Knowledge that is tacit, experiential, and embodied is an important component of an engineer's knowledge. It includes an individual's feel for the stuff s/he is dealing with—for example, one's sense of an "inch" or the order of time constant appropriate for modeling a phenomenon (Bucciarelli, 1994). The final type of conceptual knowledge identified by Ropohl is *socio-technical understanding*. This kind of knowledge has begun to transform engineering design, opening it to "systemic knowledge about the relationship between technical objects, the natural environment, and social practice" (Ropohl, 1997, p. 70). This component of engineering design knowledge expands its inter-disciplinary character beyond science and mathematics to include, for example, economics and social studies (McCormick, 1997), breaking out of the limited focus on the technical aspect of engineering-practice to incorporate organizational and cultural aspects as well (Gilbert, 1992).

Conclusion

First, a brief synopsis of epistemic elements of engineering design developed in this section. Engineering design endeavors to create artifacts in response to human needs and wants. It is best described as a practice situated in the material, cultural, social, and historical context of a firm or organization. Its practice is characterized by generation and resolution of emergent problems in a reflective conversation with the immediate circumstances of design. Its emergent nature makes it unavailable for capture in a linear process model, no matter how iterative and cyclic the model is. Design requires "knowing in action"—both procedural and conceptual knowledge specific to engineering design in addition to scientific and specific device knowledge. Design is a fundamentally social process—its products represent the intersection of participants' scenarios about the object under design. Results of experimentation and modeling provide the evidence to support design scenarios. Engineering design is inadequately explained as "applied science"—in reality, the relationship between the domains is highly interactive, interwoven, and reciprocal.

A logical next step would be a detailed analysis of classroom design activities and their comparison to the epistemic elements of engineering design derived in this section, à la Chinn & Malhotra (1999). However, doing so is not feasible given the relatively few such curricula that exist. Instead, I consider issues involved in moving elements from professional practice to the classroom.

Epistemic Elements of Professional Design in Classroom Design Activities

Research into teachers' and students' conceptions about the nature of engineering design reveal the predominant view of engineering as applied science, a view disputed by contemporary philosophers and sociologists. In mathematics and science, the challenge of changing teachers' and students' perceptions of the nature of practice has been undertaken by programs such as Modeling in Mathematics and Science (MIMS) (Lehrer & Schauble, 2000; see also Foster, 1998) and Modeling for Understanding in Science Education (MUSE) (NCISLA, 2000). Curricula developed under these programs engage students in activities reflective of professional practice, i.e., scientific inquiry and modeling. This work done in science and mathematics education provides the precedent for doing the same in technology, or more specifically, engineering design—engaging students in authentic design. Already, De Vries & Tamir (1997) point out a study by Thomson who showed changing a school curriculum in technology can change students' conceptions of the nature of technology. De Vries & Tamir advise "technology educators should think carefully about what concept of technology they want the pupils' [sic] to acquire and then see if their curriculum, through all the various activities it comprises, is supportive of it" (p. 6).

The *why* for aligning engineering design in the classroom with professional practice is given by technology education standards and sociocultural learning theory. Professional practice and classroom goals and resources drive the *form* engineering design takes in the classroom. The goal of technology literacy depends critically on developing students' understanding of the nature of engineering design and how its knowledge and products are created, i.e., its epistemology. I next discuss some of the issues that must be dealt with when importing professional practice into the classroom.

Moving From Professional Practice to the Classroom

Professional practice cannot be simply dropped into the classroom. Gustafsen (2002) warns, "technological education is not technological practice but has its own aims and criteria" (p. 3). She quotes Medway's advice to view professional practices as indicators, but not prescriptives, of curricular possibilities. Kimbell, Stables, & Green (1996) analyze some issues affecting the form of design tasks in the classroom. These issues include the balance between product purposes and teaching & learning purposes of the task; the relationship between particularized tasks and their generalized contexts; and the balance between teacher control and student autonomy. I consider each of these issues in turn.

Product versus teaching & learning purposes.

The goal of professional engineering design activity is to produce an artifact or other outcome that meets human needs. This "product purpose" must be present in classroom design activities for them to be recognizable as engineering or technological activities. Because they are set in the classroom, however, these design activities also have "teaching & learning purposes." The dual purposes may be considered as two ends of a continuum. Where the task falls on the continuum conveys the relative emphasis given to product and teaching & learning purposes, and correspondingly, determines the source of constraints and criteria for the task.

When the dominant concern is with product outcomes, Kimbell, Stables, & Green note "whoever is to be the end user of the product should properly have a significant impact on how it develops" (p. 37). Conversely, when the dominant concern is teaching & learning outcomes, the teacher will exert control over its boundaries and specifications. Kafai (1996) considers the alternate purposes to be a basic distinction between "professional design," with its focus on outcomes, and "learning design," with its focus on students' learning. She argues when the teaching & learning purpose is emphasized, "even though students may not achieve a well-rounded final product, learning can take place because of the involvement over time" (p. 73). Kimbell, Stables, & Green argue that every classroom design project should have both of these two kinds of outcomes—that the trick is to keep them in balance. Hill (1998) and Hill & Smith (1998) present a curriculum that brings students into contact with end-users of their designs; City Technology curricula (Benenson, 2001) often positions the students and teachers as end-users; solutions that give attention to product purposes.

<u>Particularized tasks versus generalized contexts.</u> Kimbell, Stables, & Green describe a hierarchy of design tasks that presents at one extreme a very open and ill-defined context, and at the other, a highly specified task; the hierarchy ranges from the "generalized context" to the increasingly "particular task". The location of the classroom design task in this hierarchy determines its degree of complexity and openness, and accordingly, the extent to which students are expected to identify their own design problems to solve. As discussed earlier, real-world design does involve problem-setting in addition to problem-solving. Perkins (1986) suggests allowing students to find, or set, their own design problems can be intrinsically motivating. Engaging in problem-setting is important for students, as is understanding the larger social, cultural, historical, and environmental context in which their design operates—both of which indicate the need

for tasks closer to generalized context. However, problems that are too ill-defined or complex can be detrimental to students' progress, as they can get bogged down trying to identify needs (Kimbell, Stables, & Green, 1996). Hmelo, Holton & Kolodner (2000) discovered the modeling and design challenge they set for students "was too large and complex for them to actually succeed in achieving it" (p. 253). A balance between open-ended and tightly-defined activities must be achieved.

A couple ways to achieve a balance include presenting students with tasks at multiple levels of open-endedness and presenting students with redesign and repair tasks or modeling and reuse tasks (Benenson, 2001). Kimbell, Stables, & Green recommend giving students design tasks at a variety of levels of more and less specificity to allow them to develop skills of deriving sensible and manageable tasks. Regardless of where the task falls in the hierarchy, it merely provides an entry point—students should be encouraged to consider its situation with regard to the levels immediately above and below it. Perkins (1986) and Mioduser (1998) suggest redesign activities afford an entry point for students into design, allowing them opportunities to problem-set in a more constrained context. In their analysis of professional practice, Youngman, Oxtoby, Monk, & Heywood (1978) report most engineering design involves modification rather than development of an artifact from scratch, establishing the authenticity of redesign tasks in the classroom.

Teacher control versus student autonomy. This issue concerns "to what extent teachers control the flow of the project or (conversely) how autonomous should pupils be in deciding what to do next" (Kimbell, Stables, & Green, 1996, p. 43). The question is who's responsible for management of the design project. The authors argue it should be a matter of students taking over responsibility as they learn how to design and how to manage their projects.

This issue has special relevance to the *process* of design. McCormick (1997) argues that the procedure for designing must be made explicit for students. However, he recommends instead of a process model, that students be taught design skills such as "generating ideas" or "evaluating designs" along with a range of techniques for each skill, plus the strategic knowledge that will guide them in deciding "when to give up generating new ideas and move on to evaluating each or choosing one, or indeed starting again to look at the design situation or problem" (p. 151). Many technology education researchers agree process models that imply a sequence of activities are not flexible enough for the work of student designers, in addition to not aligning with real-world practice (see, for example, Mioduser, 1998; Hill, 1998).

There are a couple ways to look at the issue of control and autonomy as regards developing student design capability. One way is to look at it in terms of scaffolding and fading—the teacher would support the student more heavily in the beginning and gradually withdraw that support as the student becomes more proficient. Another way is to consider the curriculum and instruction's underlying theoretical model of learning. Hay & Barab's (2001) study of two science camps, one founded on the theory of cognitive apprenticeship and the other on constructionism, revealed students experienced different degrees of responsibility for their activities under the different curriculum and instruction models. In the cognitive apprenticeship camp, students carried out specific tasks under the direction of scientists. In the constructionist camp, students were responsible for taking a project from conceptualization to completion with support from scientists. Different modes of participation yielded different learning outcomes. However it’s approached, multiple design projects facilitate students’ developing design expertise, which requires them taking increasing responsibility for managing their own design projects.

Conclusion

What’s often missing in science classroom implementations of engineering design are elements of design as an emergent, reflective, flexible process; attention to most of the elements of engineering design conceptual knowledge; explicit acknowledgement of the relationship between engineering and science at the levels of goals, activities, and knowledge; and the larger social, historical, political, and environmental contexts of design. While it’s not possible to replicate professional practice in the classroom because of constraints discussed here, it is possible to reflect epistemic elements of authentic engineering design in science classroom activities.

Conclusion and Implications

Science classrooms have begun to employ engineering design activities as a means to develop students' science understanding. Developing students' technological understanding does not emerge as an equally important objective. Using design primarily as a means to learn science runs the risk of propagating an incorrect conception of technology as applied science. The problem lies not in using engineering design to teach science concepts, but in the epistemic stance concerning engineering design knowledge, activities, and goals communicated in classroom practice. By representing the epistemology of engineering design authentically, it should be possible for the goals of technology and science literacy to co-exist.

Science educators and researchers find engineering design activities attractive in part because the activities provide for practical hands-on activity and are perceived to be a real-world use of science. However, engineering design is more than a set of skills, a process, or products—it's a culture of practice. The prototype of professional engineering design epistemology presented here can serve as a starting point for evaluating existing curricula or developing future curricula in alignment with professional practice. Although it's not possible for classroom activities to exactly replicate professional practice because of differences in the goals and resources of classroom and professional cultures, sociocultural research can guide curriculum developers in introducing engineering design practice in the classroom in a way that's commensurate with the "real world" beyond it.

Perhaps the first step in valuing engineering design for its own merit is to elevate the goals of curricula employing these activities to being overtly education *for* engineering (Gilbert, 1992). This would require making explicit the complex, interactive relationship between science and engineering at the levels of goals, activities, and knowledge. It would also require recognizing that engineering design, as a type of technology practice, has purposes and methods different from science. The relationship between science and engineering knowledge may become more apparent when engineering concepts and types of knowledge are identified and made the subjects of learning. Education *for* engineering also implies that students learn its authentic practices, the foremost among which is design. Breaking out of design process models and equipping students with heuristics for engaging in reflective, emergent design would more closely align classroom activities to professional practice. Incorporating real-world problems, users, and specifications as the sources of design challenges would not only increase the relevance of design activities, it would engage students in the type of communication, negotiation, and compromise required in professional design practice.

The next step to more fully valuing engineering design is to move from education *for* engineering to education *in* engineering, incorporating all aspects of Pacey's model of technology: technical, organizational and cultural. Doing so requires recognition of the organizational, social, historical, political, and environmental context of designs and designing. Indeed, Barlex and Pitt (2000) reflect that while engineering design's "links with science need to be appropriate ... they are not sufficient; without links to other subjects design and technology is impoverished" (p. 43).

I hope this paper is but the beginning of a conversation. The prototype of an engineering design epistemology developed here needs further research and elaboration, in terms of developing “thick descriptions” (Geertz, 1973) of professional practice and of the forms it takes in the classroom. Thick descriptions would allow a more thorough evaluation of alignment between classroom and professional design practices via a framework such as Chinn & Malhotra’s (1999).

While analysis of the epistemology of classroom design activities can tell us something about alignment of the activities, we also need to measure directly, students’ and teachers’ views of the nature of engineering as outcomes of given curricula. We don’t know how curricula are affecting their conceptions, nor do we know enough about students’ pre-existing conceptions of engineering concepts and activities to guide instruction. Other literatures describe curricula purportedly aligned with professional engineering design practice (e.g., IEEE’s Frontiers in Education Conference, technology teacher professional journals), but there is a deficit of educational research with regard to the learning that takes place in these classrooms. There’s much we have yet to learn about how students do engineering design, although several programs of research are presently at work on this (Hill, Roth, Welch, Mioduser, and McCormick and their colleagues are notable examples).

Important issues remain concerning the place of technology in K-12 education. The appropriateness of the community of practice model for technology education is an issue. As most students won’t or don’t want to go on to be professional engineers, conceiving of education as setting them on a trajectory from peripheral to increasingly central participation in the practice is contended. However, rather than eliminating technology education, this argument actually supports education *in* technology, which would prepare students for a variety of roles relative to technology as engineers, as technicians, or as citizens living in a technological world.

Regardless of the approach taken to technology education, because national standards are not directive in nature, it's effectively left to state and local school districts to choose whether or not to incorporate technology education in their schools at all. The real standards schools are subjected to are standardized assessments. Until technology is afforded the same status as a discipline of knowledge as science and mathematics and becomes an area of assessment, it may be sidelined in its quest for a piece of schools' limited resources. This would be an unfortunate outcome and counterproductive to the ongoing political, economic, and educational call for schools to increase Americans' technology literacy.

References

American Association for the Advancement of Science. (1993). Benchmarks for science literacy. New York, NY: Oxford.

Anderson, J. R., Greeno, J. G., Reder, L. M., & Simon, H. A. (2000). Perspectives on learning, thinking, and activity. Educational Researcher, 29, 11-13.

Barak, M., & Pearlman-Avinon, S. (1999). Who will teach an integrated program for science and technology in Israeli junior high schools?: A case study. Journal of Research in Science Teaching, 36, 239-253.

Barlex, D., & Pitt, J. (2000). Interaction: The relationship between science and design and technology in the secondary school curriculum. London: Engineering Council. Available: http://www.engc.org.uk/publications.

Benenson, G. (2001). The unrealized potential of everyday technology as a context for learning. Journal of Research in Science Teaching, 38, 730-745.

Black, P. (1998). An international overview of curricular approaches and models in technology education. The Journal of Technology Studies, 24. Available: http://scholar.lib.vt.edu/ejournals/JTS/Winter-Spring-1998/black.html.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. Educational Researcher, , 32-42.

Bucciarelli, L. L. (1994). Designing engineers. Cambridge, MA: The MIT Press.

Buxton, C. A. (2001). Modeling science teaching on science practice? Painting a more accurate picture through an ethnographic lab study. Journal of Research in Science Teaching, 38, 387-407.

Buxton, C. (2002). Keeping learning complex: Contextually authentic science in an urban elementary school setting. In P. Bell, R. Stevens, & T. Satwicz (Eds.), Keeping Learning Complex: The Proceedings of the Fifth International Conference of the Learning Sciences (ICLS) (pp. 33-40). Mahwah, NJ: Erlbaum.

Chinn, C. A., & Malhotra, B. A. (1999). Epistemologically authentic scientific reasoning. In K. Crowley, C. D. Schunn, & T. Okada (Eds.), Designing for science: Implications from professional, instructional, and everyday science (pp. 351-392). Mahwah, NJ: Erlbaum.

Cobb, P., & Bowers, J. (1999). Cognitive and situated learning perspectives in theory and practice. Educational Researcher, 28, 4-15.

Cross, N., Naughton, J., & Walker, D. (1986). Design method and scientific method. In A. Cross & R. McCormick (Eds.), Technology in schools, pp. 19-33. Milton Keynes, England: Open University Press.

De Vries, M. J., & Tamir, A. (1997). Shaping concepts of technology: What concepts and how to shape them. International Journal of Technology and Design Education, 7, 3-10.

Fortus, D., Dershimer, R. C., Krajcik, J., Marx, R., & Mamlok-Naaman, R. (2002, April). Design-based science and student learning. Paper presented at the National Association for Research in Science Teaching, New Orleans, LA.

Foster, S. (1998, Spring). New perspective-new practice: Curriculum as web of inquiry. Principled Practice in Mathematics & Science Education, 2, 1-10.

Geertz, C. (1973). Thick description: Toward an interpretive theory of culture. In C. Geertz (Ed.), The Interpretation of Cultures. New York, NY: Basic Books.

Gigerenzer, G. (2002, August). Cognition the fast and frugal way. Paper presented at the annual convention of the American Psychological Association, Chicago, IL.

Gilbert, J. K. (1992). The interface between science education and technology education. International Journal of Science Education, 14, 563-578.

Guralnik, D. B. (Ed.). (1980). Webster's new world dictionary of the American language (Second college edition). New York, NY: Simon and Schuster.

Gustafsen, B. J. (2002). Designing model parachutes in an elementary classroom: What counts as authentic learning? Paper presented at the National Association for Research in Science Teaching, New Orleans, LA.

Harding, J., & Rennie, L. J. (1993). Technology education in science and mathematics. In B. J. Fraser (Ed.) Research implications for science and mathematics teachers (1, Whole No. 5), 66-73. Perth, Australia: National Key Centre for Science and Mathematics.

Hay, K. E. & Barab, S. A. (2001). Constructivism in practice: A comparison and contrast of apprenticeship and constructionist learning environments. The Journal of the Learning Sciences, 10, 281-322.

Henderson, K. (1991). Flexible sketches and inflexible data bases: Visual communication, conscription devices, and boundary objects in design engineering. Science, Technology, & Human Values, 16, 448-473.

Hepburn, G., & Gaskell, P. J. (1998). Teaching a new science and technology course: A sociocultural perspective. Journal of Research in Science Teaching, 35, 777-789.

Hill, A. M. (1998). Problem solving in real-life contexts: An alternative for design in technology education. International Journal of Technology & Design Education, 8, 203-220.

Hill, A. M., & Anning, A. (2001). Comparisons and contrasts between elementary/primary ‘school situated design’ and ‘workplace design’ in Canada and England. International Journal of Technology and Design Education, 11, 111-136.

Hill, A. M., & Smith, H. A. (1998). Practice meets theory in technology education: A case of authentic learning in the high school setting. Journal of Technology Education, [On-line] 9. Available: http://scholar.lib.vt.edu/ejournals/JTE/v9n2/hill.html.

Hmelo, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. The Journal of the Learning Sciences, 9, 247-298.

Hogan, K., & Maglienti, M. (2001). Comparing the epistemological underpinnings of students’ and scientists’ reasoning about conclusions. Journal of Research in Science Teaching, 38, 663-687.

Holbrook, J. K., Gray, J., Fasse, B., Camp, P., & Kolodner, J. (2001, May). Assessment and evaluation of the Learning by Design™ Physical Science unit, 1999-2000: A document in progress. Atlanta, GA: Georgia Institute of Technology.

International Technology Education Association. (1999). Technology for All Americans. Reston, VA: Author.

Jones, A. (2001). Theme issue: Developing research in technology education. Research in Science Education, 31, 3-14.

Kafai, Y. B. (1996). Learning design by making games: Children’s development of design strategies in the creation of a complex computational artifact. In Y. Kafai & M.

Resnick (Eds.), Constructionism in practice: Designing, thinking, and learning in a digital world (pp. 71-96). Mahwah, NJ: Erlbaum.

Kimbell, R., Stables, K., & Green, R. (1996). Understanding practice in design and technology. Buckingham, England: Open University Press.

Kitchener, K. S. (1983). Cognition, metacognition, and epistemic cognition: A three-level model of cognitive processing. Human Development, 26, 222-232.

Kolodner, J. L. (2002). Facilitating the learning of design practices: Lessons learned from an inquiry into science education. Unpublished manuscript.

Knorr Cetina, K. (1999). Epistemic cultures: How the sciences make knowledge. Cambridge, MA: Harvard University Press.

Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A. (1980). Expert and novice performance in solving physics problems. Science, 208, 1335-1342.

Lave, J. & Wenger, E. (1991). Situated learning: Legitimate peripheral participation. New York, NY: Cambridge University Press.

Leach, J., Millar, R., Ryder, J., & Sere, M.-G. (2000). Epistemological understanding in science learning: The consistency of representations across contexts. Learning and Instruction, 10, 497-527.

Lehrer, R., & Schauble, L. (1999, Spring). Tackling the question: What science should students learn? Principled Practice in Mathematics & Science Education, 3, 7-10.

Lehrer, R., & Schauble, L. (2000). Modeling in mathematics and science. In R. Glaser (Ed.), Advances in Instructional Psychology: Educational design and cognitive science (Vol. 5, pp. 101-159).

Levinson, R., & Murphy, P. (1997). Science and technology concepts in a design and technology project: A pilot study. Research in Science & Technological Education, 15, 235-256.

Lewin, D. (1986). Engineering philosophy – the third culture? In A. Cross & R. McCormick (Eds.), Technology in schools, pp. 10-18. Milton Keynes, England: Open University Press.

Lewis, T. (1992, December). The nature of technology and the subject matter of technology education—A survey of industrial teacher educators. Paper presented at the annual meeting of the American Vocational Association, St. Louis, MO.

Madison Metropolitan School District. (2001). Technology education standards. Madison, WI: Madison Metropolitan School District Career/Technical Education Department.

Mamlok, R., Dershimer, C., Fortus, D., Krajcik, J., & Marx, R. (2001, March). Learning science by designing artifacts (LSDA): A case study of the development of a design-based science curriculum. Paper presented at the National Association for Research in Science Teaching, St. Louis, MO.

Martin, B., Kass, H., & Brouwer, W. (1990). Authentic science: A diversity of meanings. Science Education, 74, 541-554.

McCormick, R. (1997). Conceptual and procedural knowledge. International Journal of Technology and Design Education, 7, 141-159.

Mioduser, D. (1998). Framework for the study of cognitive and curricular issues of technological problem solving. International Journal of Technology and Design Education, 8, 167-184.

National Center for Improving Student Learning & Achievement in Mathematics and Science. (2000). High school students "do" and learn science through scientific modeling. in Brief, [On-line] 1. Available: http://www.wcer.wisc.edu/ncisla/publications/index.html#newsletters.

National Research Council. (1996). National Science Education Standards. Washington, DC: National Academy Press.

Nersessian, N. J., Newstetter, W. C., Kurz-Milcke, E., & Davies, J. (2002, October). A mixed-method approach to studying distributed cognition in evolving environments. Paper presented at the International Conference of the Learning Sciences, Seattle, WA.

Perkins, D. N. (1986). Knowledge as Design. Hillsdale, NJ: Erlbaum.

Pickering, A. (1992). From science as knowledge to science as practice. In A. Pickering (Ed.) Science as practice and culture, pp. 1-26. Chicago, IL: The University of Chicago Press.

Pickering, A. (1995). The mangle of practice: Time, agency, & science. Chicago, IL: University of Chicago Press.

Riel, M., & Polin, L. (2001, April). Communities as places where learning occurs. Paper presented at the Annual Meeting of American Educational Research Association, Seattle, WA.

Ropohl, G. (1997). Knowledge types in technology. International Journal of Technology and Design Education, 7, 65-72.

Roth, W-M. (2001a). Learning science through technological design. Journal of Research in Science Teaching, 38, 768-790.

Roth, W-M. (2001b). Modeling design as situated and distributed process. Learning and Instruction, 11, 211-239.

Rudolph, J. L. (2002). Portraying epistemology: School science in historical context. Science Education, 87, 64-79.

Rutherford, F. J., & Ahlgren, A. (1990). Science for all Americans. New York, NY: Oxford University Press.

Ryan, M., Camp, P., & Crismond, D. (2001, April). Design rules of thumb: Connecting science and design. Paper presented at the Annual Meeting of the American Educational Research Association, Seattle, WA.

Sadler, P. M., Coyle, H. P., & Schwartz, M. (2000). Engineering competitions in the middle school classroom: Key elements in developing effective design challenges. The Journal of the Learning Sciences, 9, 299-327.

Schauble, L., Klopfer, L. E., & Raghavan, K. (1991). Students' transition from an engineering model to a science model of experimentation. Journal of Research in Science Teaching, 28, 859-882.

Schön, D. A. (1983). The reflective practitioner. New York, NY: Basic Books.

Seiler, G., Tobin, K., & Sokolic, J. (2001). Design, technology, and science: Sites for learning, resistance, and social reproduction in urban schools. Journal of Research in Science Teaching, 38, 746-767.

Shaffer, D. W., & Resnick, M. (1999). "Thick" authenticity: New media and authentic learning. Journal of Interactive Learning Research, 10, 195-215.

Simon, H. A. (1969). The sciences of the artificial. Cambridge, MA: MIT Press.

Sparkes, J. (1993a). Modelling. In J. Sparkes (Ed.), Technology for technology education, p. 75-87. Reading, MA: Addison-Wesley.

Sparkes, J. (1993b). Some differences between science and technology. In J. Sparkes (Ed.), Technology for technology education, p. 25-36. Reading, MA: Addison-Wesley.

Turnbull, D. (1993). The ad hoc collective work of building gothic cathedrals with templates, string, and geometry. Science, Technology, & Human Values, 18, 315-340.

Vygotsky, L. S. (1978). Mind in society: The development of higher psychological processes. Cambridge, MA: Harvard University Press.

Wenger, E. (1998). Communities of practice: Learning, meaning, and identity. New York, NY: Cambridge University Press.

Wisconsin Department of Public Instruciton (WDPI). (1998). Wisconsin's Model Academic Standards for Technology Education.

Youngman, M. B., Oxtoby, R., Monk, J. D., & Heywood, J. (1978). Analysing Jobs. Westmead, England: Grower Press.

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