

Design and Inquiry: Bases for an Accommodation between Science and Technology Education in the Curriculum?

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Abstract: This article examines the merits of the proposition that design and inquiry are conceptual parallels. It does so by first looking closely at the inquiry-related discourse within science education, then at aspects of the design discourse within engineering, and finally within technology education. Convergences and divergences of these two streams of curricular advocacy are then identified, and implications and conclusions with respect to curriculum and instruction in both subjects are suggested.

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Background

This article examines the merits of the proposition that design and inquiry are conceptual parallels, and the prospect that this parallelism could be the basis of border crossings between science and technology education in the K–12 curriculum. This basic purpose is elaborated upon through (a) reflection on inquiry and design as creative methodological approaches in science and engineering, respectively; (b) delineation of the similarities and differences between these two approaches; (c) making the case for design as a basis for rapprochement between science and technology education in the K–12 curriculum; and (d) identification of the benefits of such rapprochement for the two subjects, and for students.

While the connection between science and technology in contemporary times is inescapable, the Hubble telescope or nuclear power plants being dramatic exhibits of this synergy, that relationship, taken as given in the public mind, has not traditionally played out in the school curriculum. As school subjects, science and technology (or technology education) have had separate existences—the former being well established and bearing high status, the latter striving for legitimacy as valid school knowledge, its status often insecure. That unfortunate tradition of

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separateness in American schools has a real possibility of changing, mainly due to the inclusion of technology as a distinct topic area in published science-content standards. Flick and Lederman (2003) editorialized that the science education community should give greater consideration to this aspect of their standards because technology can make science content reachable to those who might not be bound for 4-year college and because it often plays the role of integrating scientific and mathematical principles in daily life.

In *Benchmarks for Science Literacy*, technology features prominently as science content, with separate chapters being devoted respectively to “the nature of technology” and “the designed world” (American Association for the Advancement of Science, 1993). In the National Science Education Standards (National Research Council, 1996), scientific literacy is said to include one being technologically informed (p. 22). “Science and Technology” is included as one of the content standards, ‘abilities of technological design’ being a primary focus of this standard across grade levels. “Technology” in the science standards extends well beyond the narrow confines of computers to encompass creative human endeavors that have made possible the built environment.

As it does in the science standards, *design* features prominently in the technology education content standards (Dugger, 2001; International Technology Education Association, 2000). This new design focus in American technology teaching orients the subject more closely towards engineering, making the accommodation with science more of an imperative. The state of Massachusetts has shown the prospects for integration by renaming the subject technology/engineering, and by setting forth a joint Science and Technology/Engineering curriculum framework that features a strong emphasis on engineering design (Massachusetts Department of Education, 2001). Wisconsin and Utah are states that have refocused the subject towards engineering. To make design the core of technology education is to move the subject away from a content approach toward a process approach—embodied in the methodology of the engineer. Parallel with this process focus within technology education, manifested through *design*, is a similar focus within science, expressed as *inquiry*, the methodological approach of the scientist. Inquiry is a second pillar of the Massachusetts Science and Technology/Engineering state curriculum. This parallelism between design and inquiry is addressed in the science standards:

As used in the *Standards*, the central distinguishing characteristic between science and technology is a difference in goal: The goal of science is to understand the natural world, and the goal of technology is to make modifications in the world to meet human needs. *Technology as design is included in the standards as parallel to science as inquiry* [italics added]. (National Research Council, 1996, p. 24)

We see a counterpart of this thinking in the technology education standards as well. In the preamble to the chapter on design as a standard, it is reasoned that “Design is regarded by many as the core problem-solving process of technological development. It is as fundamental to technology as inquiry is to science and reading is to language arts” (International Technology Education Association, 2000, p. 90).

Particularly intriguing is that within the science education community, design is being increasingly viewed as a gateway to student understanding of scientific concepts (e.g., Benenson, 2001; Crismond, 2001; Kolodner, 2002). These researchers, through their projects funded by the National Science Foundation (NSF), are blurring the lines between science and technology by using design and inquiry interchangeably as pedagogic approaches, in ways that simultaneously promote both scientific and technological literacy in children. Benenson (2001) argued that

systemic reforms in science have come about because of technological demands in the society, and he illustrates how “everyday technology” could be the context for promoting both scientific and technological literacy in children. In a similar vein, Crismond (2001) engaged novice and expert designers in *investigate and redesign* tasks and found that the latter group was better able to connect the tasks with scientific principles. Kolodner (2002) used a “Learning by Design” approach to teach scientific concepts. As will be shown later in this article, her design tasks are intended as hooks for the learning of scientific principles. These attempts by researchers to explore the prospects of design as science pedagogy bode well for the realization of rapprochement with technology education.

The Inquiry-Based Advocacy Tradition in Science Education

In the discourse on reform of science teaching over the last decade, inquiry has loomed large as both content and method. “Science as inquiry” is one of eight categories of content proposed in National Science Education Standards (National Research Council, 1996). Inquiry is operationalized therein as “the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work” (p. 23). It is characterized in the *Standards* as:

a multifaceted activity that involves observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. (p. 23)

In a draft position statement on inquiry in science intended for comment by members, the National Science Teachers Association (NSTA; 2004) set forth that:

Scientific inquiry reflects how scientists come to understand the natural world, and it is at the heart of how students learn . . . Students learn how to ask questions and use evidence to answer them. In the process of learning the strategies of scientific inquiry, students learn to conduct an investigation and collect evidence from a variety of sources, develop an explanation from the data, and communicate and defend their conclusions. (p. 2)

The NSTA also proposed recommendations for how teachers should approach inquiry-based instruction, and what they should help students understand about inquiry. These understandings were to include:

That science involves asking questions about the world and then developing scientific investigations to answer their questions.
That there is no fixed sequence of steps that all scientific investigations follow . . .
Different kinds of questions suggest different kinds of scientific investigations . . .
The importance of being skeptical when they assess their own work and the work of others.
(p. 3)

Embedded in language of the *Standards* and in the NSTA draft position statement is a value that science can be taught and learned more powerfully by enactment. More than the learning of facts and principles, the inquiry focus seems geared to shaping dispositions. Inquiry is the way in

which the wonders of nature are revealed. Students follow the same inquiry trail in their classroom laboratories as practicing scientists do in their own laboratories. They learn to pose problems, gather data, make observations, evaluate findings, test hypotheses, and to communicate results. Learning is active and student centered. In the end, what inquiry seems to provide insight into is the nature of science, and the NSTA caution on this count is that the method follows the question, and not vice versa. The process is not fixed but fluid.

This current inquiry push has an advocacy tradition that is traceable to the 1960s, and can be seen in Jerome Bruner's ideas on learning by discovery. Bruner (1961) viewed inquiry as an intellectual process. Through discovery the learner became more intimately engaged in learning, and memory was thereby aided. Teaching by discovery required the learner to be a collaborator, and in this mode, he or she was more likely to pursue learning for intrinsic reasons. Bruner described discovery in its essence as "a matter of rearranging or transforming evidence in such a way that one is able to go beyond the evidence so assembled to additional new insights" (p. 22). It required focus upon the "the heuristics of inquiry," by which he meant attitudes and activities associated with finding out things. While Bruner's ideas were intended for teaching in general and not restricted to science, his inquiry heuristics were an important precursor of contemporary advocacy for inquiry science. In its general aspects, his notion of discovery can be seen to be one of the forerunners of the idea of constructivism in teaching, where learning becomes active and teaching more collaborative.

Where Bruner (1961) was advocating discovery as a general method of teaching, others in the 1960s were advocating inquiry not just as process but as the content of science (e.g., Gagné, 1963; Rutherford, 1964; Schwab, 1966). Expressing his support for the idea of inquiry as science content, Rutherford (1964) wrote "... we stand foursquare for the teaching of the scientific method, critical thinking, the scientific attitude, the problem-solving approach, the discovery method, and . . . the inquiry method" (p. 81). The subject was to be taught as a method or process rather than as content since "the conclusions of science are closely linked with the inquiry which produced them, and, conversely, that the nature of a given inquiry depends on the topic under investigation" (p. 80).

Rutherford (1964) distinguished between *inquiry as content* and *inquiry as technique*. Critical was reference to *scientific* inquiry, not merely teaching students to be inquisitive. *Inquiry as technique* was consistent with Bruner's (1961) discovery learning. *Inquiry as content* was a special case of Bruner's "heuristics of inquiry." It referred to the intellectual processes that were peculiar to particular fields of science, and crucial in the understanding of the *nature of science*. Inquiry had to include laboratory experience to show students how science was done. Students had to learn about the role of scientific theory in generating new questions and new lines of investigation. They had to understand that a result of inquiry is sometimes to reject theory.

Schwab (1966) emphasized the importance of thinking in science. His view was that *conceptions* preceded sure knowledge, and were the guiding principles of inquiry. Assuming a constructivist stance, he wrote that the knowledge derived from inquiry is interpreted knowledge. Thus, he called attention to the "conceptual principle of enquiry," by which he meant that scientific knowledge was "fragile" and subject to change. Science progresses as new techniques make it possible for new questions and new conceptions to be pursued. Schwab identified two types of inquiry: stable and fluid. Stable inquiry was doctrinal in character, coming to its limits when the scientist was confronted with contradictory data. Fluid inquiry was more speculative, the kind of science that was engaged in invention, and which could take failure in stride. Schwab advocated that laboratories were essential to school science. In the science classroom, an important purpose of inquiry teaching was to help students learn how to ask questions of the materials they study, and how to pursue answers.

Gagné (1963) raised a critical issue with respect to an inquiry approach by focusing upon its knowledge prerequisites. At what stage in a student's learning of science should inquiry be taught, and upon what conceptual foundation should such learning be premised? He expressed his entreaty thus:

There is nothing wrong with practicing enquiry, and surely enquiry is the kind of capability we want students of science to attain in some terminal sense. But practicing enquiry too soon, and without a suitable background of knowledge, can have a narrowing and cramping effect on the individual's development of independent thinking. (p. 147)

Gagné was of the view that inquiry was a critical intellectual capability to accrue from engagement with science, but that there were two other equally important and complementary capabilities, namely the ability to generalize principles to a variety of situations and the ability to evaluate the applicability of hypotheses to new problem situations. Generalizeable knowledge gave students a storehouse of principles upon which they could draw as they posed new problems. Gagné's focus on knowledge prerequisites of inquiry remains a valid issue today; inquiry teaching has to be balanced with the teaching of scientific principles and concepts. This question regarding the knowledge basis of inquiry has a counterpart in design. Like scientists, design engineers must proceed with their work from a foundation of knowledge, and this fact has to inform how design curriculum and instruction are to be approached in technology education.

From the early advocacy for the teaching of inquiry revisited here could be gleaned some foundational ideas that persist in contemporary times, including (a) that scientists integrate content and method in their work, (b) that the knowledge yielded by science is changeable over time, and (c) that inquiry can be approached simultaneously as both process and content of science.

The Scientific Method as a Contested Idea

Inquiry speaks of the disposition brought by the scientist to the quest for answers to questions provoked by curiosity. Though it is generally established that methodological approach is fundamental to resolution of questions, just what constitutes the scientific method is not settled. As indicated earlier, the NSTA position is that scientific inquiry is much more fluid than the mere following of a sequence of steps. Nobel Laureate Watson (1968) showed in *The Double Helix*—his account of the unraveling of the secrets of DNA—that where inquiry leads to breakthrough discovery, finding the pieces of the puzzle requires collaboration, multidisciplinary quest, patience, persistence, insight, immersion, changing the question, reformulating hypotheses, and sometimes following hunches that might lead to a dead end. Still, breakthrough science, like science in a high-school laboratory, must in the end conform to fundamental tenets, such as the need for meticulous documentation of process so that verification of findings by peers is made possible.

Kneller (1997) contended that while there is no single scientific method, all investigations involving a hypothesis have in common a set of activities that are very similar to the structure of everyday problem solving. This sequence includes “problem, hypothesis, inference, test, feedback, change of hypothesis, and the sequence repeated” (p. 13). The researcher observes a fact that is at odds with established theory, and this discrepancy is framed as a problem. He or she proposes a solution in the form of a hypothesis that becomes the basis of deductions as to likely results. Data are collected and are compared with the predictions. If the data and predictions are in agreement, then the hypothesis is confirmed. If not, then the researcher has a range of options

including proposing another hypothesis. Kneller noted that this approach describes some, but not all, scientific inquiry. He identified classes of scientific research in which this method is not applied since hypotheses are not invented. They include *consolidation* (validation of a stated theory), *extension* (application of a law or theory to new areas), *reformulation* (simplification of a theory to make it more applicable), and *theory construction* (creation of new laws or theory).

Variations of the basic approach suggested by Kneller (1997) can be seen in the science education literature (e.g., Chiappetta, 1997; Edwards, 1997; Greenwald, 2000). Chiappetta (1997) offered an inquiry approach to science teaching that emphasizes (a) questions, (b) science process skills, (c) discrepant events, (d) inductive activities, (e) deductive activities, (f) gathering information, and (g) problem solving. Questions originate with students, who are encouraged to pose problems of personal interest. Process skills focus on the knowledge-construction approach of scientists including stating problems, forming hypotheses, constructing inferences, conducting experiments, and communicating findings. Discrepant events stimulate students to engage in reasoning in their quest to unravel puzzles. Greenwald (2000) set forth *Problem-Based Learning* as a vehicle for teaching inquiry science. At the core of this approach is an ill-defined problem that has an initial state, a goal state, and a set of actions to get from the one to the other. Along the way, students ask questions, engage in problem-finding activities, investigate the problem, analyze results, and reiterate learning. Edwards (1997) also favored an approach to science teaching in which students “formulate their own questions, create hypotheses, and design investigations that test the hypotheses and answer the questions proposed” (p. 18).

Accounts of actual classroom experience with teaching science as inquiry now abound in the literature. Two of them are briefly reflected upon here (Edwards, Luft, Potter, & Roehrig, 1999; Thompson & Hellack, 1986) to illustrate similarity in the general methodological approach, but also prospects for variation in instructional usage. Thompson and Hellack (1986) emphasized the importance of forming and testing hypotheses. In guiding students through a fruit fly experiment, they adopted the following model of inquiry: (a) Make observations, (b) form hypotheses, (c) test hypotheses and evaluate them, (d) make predictions, and (e) test the predictions to see the generality of the hypothesis. In practice, students (a) summarized observations of fruit flies reacting to various stimuli (light, gravity, tube rotation, and tapping on tube; (b) proposed hypotheses explaining the orientation of the flies as they reacted to the different stimuli; and (c) tested these hypotheses. Edwards et al. (1999) reported using two approaches to inquiry in science instruction: technique dependent and topic dependent. In the former, students learn a technique prior to designing their own investigation. In the latter, used to help students learn to apply concepts after they have studied a unit, they develop an investigation that answers a question within a specified topic. These examples illustrate that inquiry can be used in multiple ways to help children learn science.

Conformance with the scientific method is not necessarily an assurance of good science. In actuality, human frailty must be contended within science as in other spheres of human endeavor. Scientific knowledge as objective knowledge can be contested, given that such knowledge may be conditioned by the predispositions of scientists. Driver, Asoko, Leach, Mortimer, and Scott (1994) argued that “scientific knowledge is both symbolic in nature and also socially negotiated. The objects of science are not the phenomena of nature but constructs that are advanced by the scientific community to interpret nature” (p. 5). Some scientific concepts (e.g., atoms, genes) have qualitative components that allow them to be objects of science even though they defy direct observation. Thus, scientific knowledge can be constructed and communicated among adherents, where such knowledge has both objective and symbolic dimensions.

Kuhn (1970) called attention to these essentially social underpinnings of science, contending that the acceptance of new scientific knowledge turns not so much on evidence as on whether the

scientific community is ready to reject a held paradigm. He argued that scientific revolutions have a cultural and historical component. When scientists are confronted with discrepant events, they may not always question the paradigm that led them to the anomaly. If data do not square with predictions, they may conclude that they are on the wrong track. According to Kuhn, “No process yet disclosed by the historical study of scientific development at all resembles the methodological stereotype of falsification by direct comparison with nature” (p. 77). What leads scientists to reject held theory is “simultaneously the decision to accept another” (p. 77).

In an essay that amplifies the observations of Kuhn (1970), Bauer (1992) cited several instances in scientific history where findings were ahead of their time, and not accepted. He further pointed to actual instances where the calculations of scientists were different from experimental values, and where the right decision was to trust the calculations. Drawing on the race to the discovery of the structure of DNA, he showed how Watson and Crick (as cited in Bauer, 1992) made allowances for experimental error in their data. He stated: “Evidently, then, some of the most successful chemists have not practiced the proper scientific method, which is supposed to put evidence first and theorizing second” (p. 23).

Bauer (1992) showed that even within a single scientific discipline, there can be variation in methodological approach, an example being the field of chemistry with its many “tribes,” each with its peculiar inquiry approach. Variation also exists across disciplines, with geologists, biologists, physicists, and chemists pursuing peculiar methodological lines. Such variation may include the way in which they use mathematics. Some are observational while others are experimental. Some (e.g., geology) are data driven while others (e.g., astronomy) are theory driven. Some are quantitative, and others qualitative.

Whatever the discipline-based variations in approach, the way in which scientists conduct and report their work determines the credibility of their findings and how well they are received. We see this in the commentary of Nobel Laureate Richard Feynman (1999) on the criticality of methodological approach in the quest for scientific knowledge. Foremost is the requirement that the scientist not know the answer beforehand, and therefore having to approach the work with doubt and uncertainty. When evidence is found it has to be judged, and here the scientist has to be careful not to cherry-pick but to consider the totality of observations. Authority could be relied upon when judging evidence, but should be disregarded if observations disagree with it. Results must be reported in a disinterested way, not slanted in the service of a view that is not suggested by observations. Feynman dwelled on how vital a role integrity must play in this. He explained:

For example, if you're doing an experiment, you should report everything that you think might make it invalid—not only what you think is right about it; other causes that could possibly explain your results; and things you thought of that you've eliminated by some other experiment, and how they worked—to make sure the other fellow can tell they have been eliminated.

Details that can throw doubt on your interpretation must be given if you know them. You must do the best you can—if you know anything at all wrong, or possibly wrong—to explain it In summary, the idea is to try to give all of the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another. (p. 209)

More than procedural steps, the tenets to which Feynman (1999) called attention are the ethical underpinnings of the scientific mode of conduct. Doubt, uncertainty, an open mind, the preeminence of data, the maintenance of distance in the reporting of findings, and calling attention to possible flaws in one's approach are all habits that safeguard against bias and that improve the chances of advancing knowledge.

Inquiry Research in Science Teaching

In the previous section, examples of inquiry in classrooms were drawn upon as part of the discussion of the contested nature of the scientific method. In this section, research on inquiry in science teaching is examined briefly in two dimensions: (a) in situ observation of inquiry teaching and (b) teacher conceptions and dispositions. Studies were chosen because they provided insight into fundamental issues relating to inquiry teaching and reflected in the discussion thus far, including conceptions of the scientific method held by teachers, the efficacy of professional development or other intervention activities intended to foster conceptual change in teachers, the nature of the teacher/student engagement when inquiry is taught, and the fit between inquiry in actual classrooms and advocacy as reflected in the reform-oriented discourse.

The in situ studies focused on accounts of teachers engaging their students in inquiry learning (Mackenzie, 2001; Polman & Pea, 2001; Toth, Suthers, & Lesgold, 2002). These studies revealed a strong constructivist dimension to the teaching of inquiry, including the encouragement of students to pose questions, collaborate with each other in groups, and to share findings. In one study, the teacher's strategy was to assume the stance that scientific questions must engender a sense of wonder. Students were challenged at points within inquiry lessons to generate such questions in relation to their class activities (Mackenzie, 2001). One teacher used *transformative communication* as the strategy to engage students in inquiry learning. This approach entailed open-ended science inquiry in a way that allowed for expression of the voices of both teacher and student. The teacher coached students through the inquiry process by observing their "moves," reinterpreting them, and encouraging them to pose questions. Gradually, as teacher and students came to mutual insights, learning occurred as initial moves were revisited (Polman & Pea, 2001).

Toth et al. (2002) examined the effectiveness of translating Web-based information into two forms of representation: evidence maps and prose. The subjects were ninth-grade science students. The researchers first conducted inservice professional development for the teachers, emphasizing student-centered, collaborative learning. The classroom approach was to work collaboratively with teachers, placing students in teams to work on problem-solving challenges. The authors found positive results for the effects of representational guidance using evidence mapping, and explicit reflection.

The studies that examined teacher conceptions and dispositions regarding inquiry yielded equivocal findings. In some, the view of scientific inquiry was informed (Crawford, 1999; Lederman, 2000) while in others it tended to be stylized (Tamir, 1983, Weinburgh, 2003; Windschitl, 2002). But the evidence also is that conceptual change could be effected in teachers if they are exposed to enabling professional-development activities, such as reflective activities, or engagement with actual scientists (Weinburgh, 2003; Windschitl, 2002).

Tamir (1983) found that experienced teachers were more inclined than novice teachers to associate inquiry with scientific research, though both held stylized views. He noted:

It is interesting to note that certain cornerstones of science as inquiry, such as the history of scientific ideas, the tentativeness of scientific knowledge, doubts, conflicts, personalities, and personal experiences of scientists are mentioned neither as associations nor as parts of definitions. The image of science as inquiry which emerges is, by and large, that of a systematic step by step process based on observations and experiments which give results that are to be interpreted and which lead to conclusions and scientific laws. There is no mention of the fluid nature of science. (p. 661)

Weinburgh (2003) observed conceptual change in the way a group of middle-school teachers depicted the scientific method (through concept maps), after they had observed and interacted with

actual scientists in action, and reflected upon the experience. Where initially they were inclined toward linear depiction of the process, they later produced renderings illustrative of an iterative process with feedback loops. Windschitl (2002) investigated how the inquiry experience of preservice teachers in a science-methods course influenced their thinking about classroom practice. The teachers maintained journals reflecting on their inquiry journeys. They wrote descriptions of the relationship between the phases of inquiry and created metaphors for inquiry. Findings were that the participants who had the more authentic views of inquiry after the inservice experience were those who had prior science-research-project experience in their undergraduate course work.

Crawford (1999) found that novice teachers could successfully construct an inquiry-based environment for science learning, especially where inquiry is interpreted as teaching to help students pose and answer important questions, employing techniques similar to that of scientists. Whether teachers' understanding of the nature of science affected classroom practice, and identifying the factors that impeded the effects of such understandings on practice, were questions guiding the work of Lederman (1999). The findings were consistent with the view that scientific knowledge is tentative, premised upon human creativity and imagination—that it was essentially subjective, being theory laden though based on empirical evidence. Teachers also understood the difference between observation and inference; however, their conceptions did not appear to influence their practice.

The studies briefly reported here provide glimpses of the challenge inherent in translating inquiry advocacy into actual classroom practice. A role for professional-development activities is shown, such activities causing teachers to change their perspectives. Also evident is the degree of correspondence between advocacy and practice with respect to pedagogic approach. In the inquiry classrooms seen here, teachers empowered their students by challenging them to pose questions, to work collaboratively in groups, to engage in student–teacher dialogue, and to report findings. The research also highlights the challenge of bringing all science teachers toward an acceptable view of what constitutes scientific inquiry, and getting them to conduct their teaching practice accordingly.

Design

As indicated earlier, design features prominently in the American standards for teaching technology in Grades K–12 as the predominant approach to teaching the subject (International Technology Education Association, 2000). This section of the article explores the nature of design by examining the way it is employed by engineers as they seek solutions to practical problems. Design also is part of the craft tradition, but it is engineering and not craft that inspires the standards for teaching technology. How design is viewed within the subject, including research evidence, also is explored.

Variations on the Design Method

As with inquiry, where variations of a basic quest for answers can be seen across scientific disciplines, within engineering such variations of a general design method also are evident. A well-known conception is that offered by French (1999), in which the design process is shown to be iterative rather than linear, and comprised of a (a) need, (b) problem analysis, (c) statement of the problem, (d) conceptual design, (e) selected schemes, (f) embodiment of schemes, (g) detailing of solution, and (h) working drawings. Conceptual design is the heart of the process. French wrote that it is

the phase that makes the greatest demands on the designer, and where there is the most scope for striking improvements. It is the phase where engineering science, practical knowledge, production methods, and commercial aspects need to be brought together, and where the most important decisions are made. (p. 3)

Conceptual design features as a significant stage in “systematic design,” as set forth by Pahl and Beitz (1995). These authors divided the design process into four main stages: (a) product planning and task clarification, (b) conceptual design, (c) embodiment design, and (d) detail design. The trigger is customer need. They characterized conceptual design as

that part of the design process in which, by the identification of the essential problems through abstraction, by the establishment of function structures and by the search for appropriate working principles and their combination, the basic solution path is laid down through the elaboration of a solution principle. (p. 139)

They noted that this aspect of design includes an abstraction phase intended to push the designer away from fixation and conventional solutions. The designer focuses on the general and essential rather than the particular or incidental. He or she determines function structures, which are decomposed into subfunctions. Working principles are developed for subfunctions, and these are combined into a *working structure*. When made concrete, the working structure leads to the solution principle. This stage of design involves theoretical ideas along with the physical process, and geometric and material characteristics. It leads to several solution possibilities called a “solution field.” These solution variants have to be evaluated to ascertain which would lead to the technical product.

Kroll, Condoor, and Jansson (2001) divided the engineering design process into three phases: need identification, conceptual design, and realization. Need identification is concerned with functions and constraints. Function is the main purpose of the design. Constraints are boundaries or limits on the solution space in which the designer searches, as he or she seeks to head off downstream design issues. Five types of functions/constraints are identified: performance, value, size, safety, and special. The designer considers *trade-offs*, such as value versus performance. The process for considering functions and constraints is not sequential. The designer may backtrack if need be. These authors contended that conceptual design is more difficult than other stages of design.

Koen (1985) proposed an “engineering method” that was informed by *heuristics*. Heuristics do not guarantee a solution to design problems but they can aid in design by reducing the search time. In Koen’s view, they control much of the work of engineers. Heuristics really are a type of long-term memory schema that engineers have at the ready, so they can minimize cognitive expenditure when they come to familiar terrain. Many bridges have been built and their processes documented; thus, faced with the design of a bridge, the engineer relies upon heuristics for familiar aspects so that his or her creative energies can be devoted to novel aspects of the job at hand. Koen identified five categories of heuristics: (a) orders of magnitude, (b) factors of safety, (c) attitudes to work, (d) acceptable risk, and (e) resource allocation. For a mechanical engineer, one rule of thumb is that a bolt should have one and a half turns in the threads. For a chemical engineer making a heat transfer calculation, a valuable heuristic is that air has an ambient temperature of 20 degree centigrade and an 80:20 mixture of nitrogen and oxygen.

A challenge for the designer who has come to the end of the conceptual design stage is how to evaluate the possible solutions. For this, Suh (1990) offered *axiomatic design*. Suh wrote that design consists of two distinct processes: a creative process in which new ideas are synthesized

and an analytic process in which proposed ideas must be evaluated. The creative process “depends strongly on the designer’s knowledge base and creativity, and is subjective” (p. 9). This process can yield an infinite number of solutions. By contrast, the analytic process is deterministic. The two processes are interrelated, and axiomatic design is a way to normalize the relationship between them.

Suh (1990) proposed two design axioms: (a) the independence axiom, which says to “Maintain the independence of functional requirements;” and (b) the information axiom, which says to “Minimize the information content” (p. 72). The first axiom separates feasible from unfeasible design while the second selects the optimum design solution from among those deemed feasible. Together, these axioms impose constraints on the design.

Arriving at a methodology that can aid in the evaluation of multiple design options is a challenge in engineering. One evaluative scheme is that offered by Hubka (1982) and is comprised of a rubric through which points are assigned based on suitability. Morphological evaluative techniques have been set forth (e.g., Hubka, 1982; Pahl & Beitz, 1995) in which a matrix arrays the various functional requirements on one axis against all design options on the other. Suh (1990) noted that such evaluative processes fall short of offering rational design solutions, and that axioms help to streamline what otherwise are hit-and-miss processes. In an illustration of axiomatic design, Sekimoto and Ukai (1994) described their basic design approach in which the designer first sets forth functional requirements for the product and then begins development of its physical embodiment. Functional requirements are mapped onto design parameters in a design matrix. Such a matrix can be constructed for each possible solution. The independence and information axioms are used to arrive at the design.

Cross and Cross (1998) provided phenomenological insight into the nature of design expertise. Two expert designers were interviewed about their approach, and from their reflections three common strategies emerged: (a) taking a systemic approach to the problem, (b) framing the problem in some distinctive way, and (c) designing from first principles. A systems view means taking the design problem holistically. Thus, in designing a backpack, one expert considered the rider, the bicycle, and the backpack as a single entity. The problem was framed in terms of maintenance of stability. In the search for a rigid structure, the first principle of triangularity was drawn upon. One revelation from this study is that in practice, expert designers do not follow standard stepwise procedures. Further, the authors were impressed that even though they could arrive at common themes underling the approach of the experts, it was clear that the design process was messy and difficult to document.

This look at design conceptions illustrates that engineers proceed along roughly similar paths when they do their work. Once they frame the problem, they engage in divergent thinking in search of possible solutions. This quest is bounded by constraints including cost, safety considerations, social factors, and the present state of the art. Previous experience is drawn upon through the employment of heuristics in a way that frees cognitive resources that can be devoted to finding the eventual solution. The final choice of solution requires evaluation-based decision making. The journey from initial framing of the problem towards arrival of a final design solution is nonlinear.

Design in Technology Education

Design had been an established feature of technology education in schools in the United Kingdom before it took hold in the American version of the subject. As Wright (1993) noted, design was added to the Craft Design Technology (CDT) phase of the subject in the United Kingdom after 1975, designing/making being a critical curriculum nexus. Design features

prominently in the version of the subject (Design and Technology) that was included in the U.K.'s National Curriculum. Four Design and Technology "attainment targets" make up the core of that curriculum (see Department for Education, 1990). The first target focuses upon need identification and opportunities. Students are expected to identify design opportunities in contexts such as home, school, and community. The second target is "generating a design." It requires students to "generate a design specification, explore ideas to produce a design proposal and develop it into a realistic, appropriate and achievable design" (p. 7). Of interest here is that the motif of the Design and Technology curriculum in the U.K.'s National Curriculum is a generic design process—finding a need, generating the design, planning and making (the design embodiment), and evaluating design efforts. Design in the British curriculum, as characterized earlier, has strong craft origins, though the basic design framework is partial both to craft as well as engineering traditions, and indeed allows for context-independent problem solving in everyday situations and contexts that range far from engineering.

Commenting on the teaching of design in the British curriculum, McCormick and Davidson (1996) cautioned that teachers were giving precedence to products over process. Wilson and Harris (2003) examined best practices in teaching and learning of design and technology in England and Wales, finding some support for the teaching of procedural skills and, generally, of intellectual skills. But one does not see in this comprehensive review of design practice in the schools any special focus on the design methodology as technological content. Other observers of the teaching of design in British schools cautioned that teachers were pursuing a simplistic line when doing so, following a design model comprised of stages that was often contrary to the natural design tendencies of children (e.g., Chidgey, 1994; Johnsey, 1995). Proposing alternatives to design as pedagogy for technology education, Mawson (2003) acknowledged that design as a process had become a standard approach to the teaching of the subject in England, Australia, and New Zealand, with *design-make-appraise* being the common motif.

Design has within recent years become a more explicit provision of technology education in the United States, emerging after a period in the 1980s and 1990s in which the focus had been on a content- or discipline-based approach to curriculum. Savage and Sterry (1990) proposed the technological method as an essential aspect of a framework for teaching technology. Similar to Design and Technology in the British National Curriculum, the basic motif of design was a sequence of steps inclusive of (a) problems and opportunities springing from human needs and wants; (b) technological processes, namely analyzing, realizing, and testing; (c) evaluation; and (d) solutions and impacts. Drawing upon cognitive science research, Johnson (1992) proposed an intellectual-processes approach to teaching technology, with focus on meta-cognition and creative problem-solving skills. He called particular attention to the consonance between the intellectual-processes approach he was advocating and technological problem solving as follows:

Because technology education content is often taught through a problem solving method . . . technology teachers need to act like technologists in their classrooms. They need to solve unfamiliar technological problems for students and not be afraid to make errors or have difficulties finding solutions. By serving as a role model, technology teachers can show students how to collect and use information to solve technological problems and help them realize that not all problems have straight forward and simple solutions. (p. 34)

This process approach has become the status quo in American curriculum thinking, embodied in design with its problem-solving concomitant. It can be seen in a contribution by Warner (2003), who dwells on creative components of design and upon what teachers can do to enhance its expression, contended that "the very nature of the thinking processes involved in design may run

contrary to the traditional structures encouraged in most school curricula” (p. 7). Design stands at the core of the Standards for Technological Literacy (International Technology Education Association, 2000). More importantly, these standards have the explicit imprimatur of the American engineering establishment, as can be seen in the commemorative foreword of the standards written by the President of the National Academy of Engineering. The standards make clear that the design logic of the curriculum is premised on the work of engineers, not artisans. How engineers approach design is set forth as follows:

The development of a technology begins as a desire to meet a need or want. These needs or wants could belong to a single inventor or be shared by millions of people. Once needs or wants have been identified, the designer must determine how to satisfy or solve them. The modern engineering profession has a number of well developed methods for discovering such solutions, all of which share common traits. First, the designers set out to meet certain design criteria, in essence, what the design is supposed to do. Second, the designers must work under certain constraints, such as time, money, and resources. Finally, the procedures or steps of the design process are iterative and can be performed in different sequences, depending upon the details of the design problem. (p. 90)

The open-ended design problem has become common in technology education teaching (e.g., Bame & Booth, 2000; Warner, 2003), where students employ divergent-thinking techniques to identify an array of possible solutions and then decide on one that they eventually explore and develop. These problem-solving episodes often reflect design only superficially. As Burghardt and Hacker (2004) noted, they typically sidestep technical aspects of the conceptual design phase such as the use of mathematics to predict performance, or engagement with the requisite science. How to reconstitute the current prevalent problem-solving approach so that it more accurately reflects the design processes of engineers in its technical aspects is a challenge that technology education has begun to address.

As indicated earlier, the state of Massachusetts has been a leader in embracing the engineering design bent of the technology education standards. The state’s *Science and Technology/Engineering Curriculum Framework* curriculum guide (Massachusetts Department of Education, 2001, p. 73) proposes an eight-step design process as follows:

1. Identify the need or problem.
2. Research the need or problem.
3. Develop possible solution(s).
4. Select the best possible solution(s).
5. Construct a prototype.
6. Test and evaluate the solution(s).
7. Communicate the solution(s).
8. Redesign.

Step 2 in this schema has potential for bringing into play the requisite science or mathematics, as illustrated in Cotton (2002). Step 4 requires evaluation of designs. It moves the pedagogy from a problem-solving approach to a design approach. As discussed previously, selecting the best solution from an array of possibilities is a difficult technical proposition in the real world of engineering. It is a dimension of the teaching of design where there is room for much development. What should students be taught about making evaluative decisions about designs? How should they be taught to arrive at the best design? These are questions that until now have not been fully explored in the design-related literature of technology education.

Blurring the Science/Technology Education Boundaries through Design

Design is being employed in classrooms in ways that are bringing science and technology education closer together. Two frameworks that are making this possible are (a) science through design and (b) design through science.

Science through Design

The design literature in technology education includes accounts of attempts to employ design as a vehicle for teaching scientific content (e.g., Burghardt & Hacker, 2004; Koch & Burghardt, 2002; Kolodner, 2002; Zubrowski, 2002). Zubrowski (2002) proposed a model that would integrate scientific content into the process of children learning technological design. The model is comprised of three phases. In the first there is exploration, in which students brainstorm ideas about building a functional artifact. The second stage involves them putting aside preliminary constructions and considering a standard model that is a synthesis of class ideas. Students conduct systematic tests (controlled experiments) at this stage. In the third phase, they go back to an open-design process in which they can incorporate ideas they have gained in considering the standard model, or they can arrive at a completely new design. Zubrowski recounted how this process worked in a class where students were challenged to attach a cup and a string to the rotating arm of a windmill to allow it to lift weights. Students engaged in the trial-and-error phase, then worked on a standard model to the point where essential features of a functional windmill were yielded. They then went back to designing on their own, improving their individual designs as they saw fit.

Kolodner (2002) employed a Learning by Design (LBD) approach in which the design process in technology education is used as the vehicle for teaching science concepts. She reported results showing that LBD students outperform non-LBD peers in ability to design experiments, planning for data gathering, and collaboration. Students learn science by engaging in technological design. Kolodner asserted that “construction and trial of real devices gives students the opportunity to experience uses of science and to test their conceptions and discover the bugs and holes in their knowledge” (p. 18). Her process includes two learning cycles: (a) a “design/redesign” cycle, in which students “mess about” and (b) “investigate and explore.” In the latter stage, students make predictions about the performance of their designs. They run experiments and gather data.

In one example Kolodner (2002) provided, students learned about Newton’s Law on equal and opposite forces as they considered the design of a balloon-powered car. From this, they returned to the design-planning phase to deal with the constraints and the criteria of the design challenge. They then built and tested cars, using scientific-content knowledge to predict the performance of their design. Kolodner indicated that a critical aspect of her LBD approach is having students learn to reflect upon and refine their reasoning ability. Sharing and refining ideas publicly with peers is a key feature of the approach.

Burghardt and Hacker (2004) described an “informed design” approach, which is unique in the extent that the investigation stage requires students to become engaged with “Knowledge and Skill Builders (KSBs).” Basically, this is a research phase in which students must delve into the mathematics, science, or other skills that underpin the design. Thus for bridge-building projects, common in technology education but typically taught without due inclusion of underlying science and mathematics content, KSBs would include investigation of types of bridges, and tension and compression in bridge members. A similar line to design is taken by Cotton (2002), who illustrated how the trial-and-error design strategies ordinarily seen in technology education classrooms can be replaced by a more rational approach in which students use mathematics to predict the efficacy

of their solutions. Likewise, Koch and Burghardt (2002) showed how mathematics and science constraints are made a part of design challenges that elementary teachers must develop as part of professional development. In coming to grips with the challenges, their students must demonstrate understanding of the relevant mathematics and scientific principles by infusing them into their solutions, and by explaining the reasons for their choice of solution.

Design through Science

Parallel to accounts of design approaches that enhance science learning are those that show how science becomes the vehicle for prompting design. These approaches are consistent with a problem-based learning pedagogy (e.g., Greenwald, 2000). One such case is that reported by Snetsinger, Brewer, and Brown (1999), in which an inquiry project for middle- and high-school students began with the question “How can one harness the energy of the wind to create electricity?” (p. 39). Teams of students tackled the challenge. They tested and refined their solutions using a household fan as the wind source. They further developed a turbine that could turn a shaft to create electricity and a generator that yielded rotating mechanical energy. The wind-machine designs were tested by manipulating variables. Relationships between wind velocity, blade size, blade angle, and electrical output were explored.

Subramaniam (1999) described a practical physics activity in which students studied the behavior of bimetallic strips when heated. Once students understood expansion and contraction, they used the knowledge to design practical appliances for the home, such as pancake flippers, and a self-heating fish tank. The approach allowed students to see the relationships between the physics concepts of heat, elasticity (Hooke’s Law), mechanics (conservation of energy and machines), and electricity (electric circuits).

Reiva (2000) reported on a high-school project in which students assessed the energy efficiency of a building. They made observations noting areas where energy was wasted and recorded findings. The energy audit raised the question of heat flow in the building and led to recommendations involving the replacement of bulbs that would produce less energy and save money. The author noted that “when a science curriculum is project-based, students become immersed in real problems, think creatively, and reach for high standards” (p. 47). Also drawing on the everyday environment as the source of learning opportunities, Bachtta (2001) reported on a classroom activity in which students observed examples of the use of concrete, making observations about its properties. They then launched into an investigation of the making and testing of concrete. Students were arranged into teams, each charged with the puzzle of designing and creating a concrete sample that could resist the strongest compressive force. Variables included water, type of reinforcing materials, and aggregate size. Students generated questions based on these variables, such as: “What would happen if a different liquid was substituted for the water?” (p. 42). They then manufactured the concrete sample and tested specimens, making qualitative and quantitative observations. They calculated the efficiency of the slab and then discussed findings.

Whether the approach is science through design or design through science, the effect is the same: that areas of convergence between the science and technology are exploited in school in ways that mimic complementarities we see between the two in the real world.

Research on Design in Technology Education

Design has been the basis of research in technology education from the standpoints of teaching as well as learning. Some studies have focused on design from the perspective of

preservice teachers of technology (McRobbie, Stein, & Ginns, 2001; Parkinson, 2001). Parkinson (2001) examined preservice teachers' understanding of structures. They had to design and make a structure that would span a gap which could be traversed by a simple vehicle. Materials were paper clips and sheets of paper. The students seemed to have incomplete understanding of how a structure can push back against a force. Another misconception was that paper is not strong. Parkinson suggested that this task was an example of how science and technology could be mutually reinforcing. McRobbie et al. (2001) examined preservice teachers as novice designers, mapping their reasoning process. They found a lack of fit between generic step-by-step models and how the teachers actually approached the design tasks. The reasoning approach employed by the teachers followed a "see-move-see again" process (p. 109). The authors found the design process for these teachers/novice designers to involve the interplay of tools, materials ideas, and people.

Other studies have focused upon the design ideas of students in the elementary grades (e.g., Druin & Fast, 2002; France & Davies, 2001; Gustafson, Rowell, & Rose, 2001; Hill & Anning, 2001; Hutchinson, 2002; Rogers & Wallace, 2000; Welch, 1999). Rogers and Wallace (2000) found that elementary children confused the difference between drawing a picture and making a design drawing, and that they did not see the connection between their designs and making a design drawing. These authors suggested that special approaches to teaching design might be necessary for the elementary grades. Gustafson et al. (2001) studied the ideas offered by children aged 5 to 13 years on how a structure could be strengthened. The students had many good ideas prior to instruction, the quality of which did not improve with instruction. They concluded that children's understanding could be improved through classroom experiences that increase their knowledge in the underlying scientific concepts such as strength, hardness, and elasticity.

Doornekamp (2001) examined the importance of well-considered teaching materials, finding that when students are at the beginning stages of learning, a structured approach to constrained design problems is best. When they have acquired more experience, open-ended problems can be considered since students have acquired the requisite conceptual knowledge. Welch (1999) studied seventh graders, who were unschooled in any design process, as they engaged design tasks. The students were given a sheet of paper, and the task was to construct the tallest possible building that could stand for 30 s. Codes were developed to map their reasoning process. The researchers found that the strategies students used were complex and not linear. They included using serial strategies, trying out then abandoning solutions and moving on to the next solution. Modeling in three-dimensional materials was an important aspect of their solution process, featuring in their understanding of the problem, generating solutions, and testing and improving solutions (p. 31). This study, like that reported by McRobbie et al. (2001), contested the idea of a stepwise problem-solving approach to design. The finding was that left to their own devices, students would tend toward solution strategies that deviated markedly from the generic-design script. This, it turns out, is consistent with the approach of expert designers (Cross & Cross, 1998).

Design and Inquiry; Convergences and Divergences

The discussion thus far has examined how the processes of inquiry and design are perceived in the scientific and engineering communities, respectively, and how they are reflected in the school curriculum through school science and through technology education. The question to be addressed next is just how much are these two processes conceptually similar, and in what ways are they not?

Convergences

Design and inquiry are reasoning processes, ways in which engineers on one hand and scientists on the other come to terms with puzzles and uncertainties that confront them—puzzles or uncertainties that can be thought of as *problems*. They are navigational devices that serve the purpose of bridging the gap between problem and solution. In both cases, the path from problem to solution may require backtracking, including restatement of the problem, as the engineer or scientist comes to dead ends or as they are able to rule out the likelihood that a particular pathway can be fruitful. Accordingly, both design and inquiry conform to Newell and Simon's (1972) insights regarding the nature of a solver's search through a problem space, during which there is expansion of knowledge of the problem situation, until a solution is found. Both the engineer and the scientist must reevaluate their representation of the puzzle that occupies them as they move toward solution, and in the process of so doing, both would find working memory to be limiting and instead come to rely upon a variety of schemata (Hunt, 1994).

While some design and inquiry problems are in the realm of the routine, at the more challenging end of the spectrum both types tend toward being ill-structured and characterized by uncertainty. *Uncertainty as a starting reasoning condition* is indeed a common signature of both processes, one that requires in both cases the systematic ruling out of extraneous variables. Uncertainty as a common contextual condition also makes both design and inquiry fundamentally creative processes that demand expenditure of cognitive resources in the form of search strategies.

As they engage in search, both the engineer and the scientist must rely upon like cognitive-reasoning tools, such as *brain storming* or *analogical reasoning* during the search stage (e.g., Hallyn, 2000; Koen, 1985). At the conceptual-design stage, the engineer finds that the search process is aided greatly by postponing engagement with the physical realm and resorting to abstraction. Here, the quest is for the principle of the design. This is akin to the role that theory plays in scientific inquiry. Theory helps the scientist to narrow the pathways to solution. Through hypotheses informed by theory, the scientist avoids mere random search, and instead engages in more purposeful quest.

Engineers and scientists resort to mental models and often *visual representation* of their ideas as a means both of rehearsing and communicating thought. The scientist may utilize graphics to work out chemical structure. The engineer may use graphics in the form of line drawings or sketches to illustrate the workings of a particular design—testing whether components fit together. Beyond graphics, it is often necessary in design as in inquiry to create three-dimensional models of solutions that aid greatly in the reasoning process. Such models played a vital role in Watson and Crick's (as cited in Bauer, 1992) final push to discovery of the structure of the genetic code. Engineers can use mock-ups to provide insight that can then be transferred to the construction of prototypes.

In the late stages of search in both design and inquiry, there is need for *testing*, evaluation, and decision making. In design, the issue is which of a narrow set of solution alternatives best conforms to design parameters; for inquiry, the question is how do the empirical data compare to hypothesized results, and the need for care that the totality of observations are reported and not just results that are favorable. Beyond the conceptual similarity that attends the evaluation stages of design and inquiry is the fact that for both processes, this stage bears co-equal critical weight.

While inquiry and design are often reduced to generic procedures, and are taught as content in their own right, it seems clear from the respective literature that in practice both these processes depend upon *content knowledge*. Confronted with a challenging design problem, the engineer must draw upon a base of knowledge that might include requisite physics or mathematics,

materials, techniques, engineering codes and standards, an array of design heuristics, patent histories, components, and the state of the art. A knowledge base of this order becomes part of the raw material of creative thought. Like the engineer, the scientist engaged in inquiry does so by drawing upon a reservoir of knowledge. In *The Double Helix*, in which Watson (1968) described the quest for understanding of the genetic code, he and colleagues brought to bear a store of foundational scientific knowledge from a variety of fields including genetics, biology, chemistry, and physics. Gagné (1963) made clear that scientific conceptual knowledge must be the foundation of inquiry.

Design and inquiry converge as processes in the extent that both proceed under constraints. For the engineer, the constraints include cost, the state of the art, safety, or environmental considerations. For the scientist, constraints also might include safety factors in cases where the materials (e.g., some types of viruses or chemicals) with which they are working can be hazardous to human health and well-being. Scientists also must subject their work to ethical tests. Stem cell research may bear promise for some forms of human affliction, but scientists who work in this area must do so under stringent ethical regimes.

The work of engineers and scientists converge on an operational level in their approach to resolution of day-to-day questions on their way to answering or asking bigger questions that could advance their work (G. Salinger, personal communication, August, 2004). They must both engage in forms of trial, error, and reflection, learning from failure, and making adjustments in their hypotheses and in their lines of approach. In their resolution of the small, day-to-day questions, inquiry and design bear resemblance.

Finally, engineering design and scientific inquiry have in common that they are both constrained by paradigmatic thinking. Kuhn's (1970) observations regarding the cultural and historical dimensions of change in science were discussed earlier. In a similar manner, basing his observations on case studies of engineering error through history, Petroski (1994) showed that change in engineering often comes through failure caused by human error, such error often lying latent within what appears to be engineering success, waiting for the right set of events for failure to reveal itself. For example, the error might lie in the accepted design approach to one structural aspect of the approach to bridge design. Only with failure comes wholesale reevaluation of extant practice. Petroski cited as an example the impact of the Challenger disaster in 1986 on the approach to the design of spacecraft and on the management of their launching.

Divergences

While design and inquiry converge on many dimensions, as indicated earlier, these processes also diverge. A few important areas in which they do include purpose, role of trade-offs, role of failure, role of context, and practicality tests.

Purpose. A major area of divergence between design and inquiry is in their purposes. Scientific inquiry has pure and applied dimensions. Applied science is instrumentally inspired, as in the search for cures for diseases or the development of resistant varieties of food crops. Pure science is inherently speculative, fueled more by curiosity—by the pure desire to try to unravel secrets of nature. In this vein, such scientists are interested in the behavior of some materials under cryogenic conditions. Others are interested in probing the geologic record of Mars to understand better how that planet evolved, with such knowledge in turn illuminating our understanding of how Earth might evolve. Unlike scientific inquiry, design does not have a purely speculative component. The purpose is invariably instrumental—inventing an artificial heart, minimizing structural failure in an earthquake zone, or constructing a tunnel that improves the movement of people.

Because of divergence of purpose, the questions that are the starting point of scientific inquiry must be of different character from those prompting design. The engineering design challenge posed by the Hubble telescope was how to get it to provide as clear a view as possible back in time. Scientists using the Hubble for inquiry are interested in large, fundamental questions relating to origins of the universe. Whereas in scientific inquiry one speculates on grand questions such as how the universe evolved or the extent of global atmospheric warming; engineering design deals with questions that are more grounded such as why did a particular bridge fail or how to retrieve oil from particular geologic formations.

Role of Constraints. While both scientists and engineers do their work against the backdrop of constraints, the effect of constraints on the work of engineers is arguably more telling. Constraints (e.g., time, costs, laws, building codes, or aesthetics) impose restrictions on the designer by suggesting practical boundaries within which the search for solution must occur. These restrictions are in fact invitations to creativity. The essence of design is embodied in the ability of designers to overcome imposed restrictions through creative solutions. Automobiles of today must meet exhaust-emission, fuel-efficiency, and safety standards, among others. Constraints of this order tax the creativity of engineers who, in addition to working within them, must also try to keep costs down for the consumer. While scientific inquiry must take into account limiting constraints such as cost, these considerations are not as intrinsically woven into scientific reasoning as they are into design reasoning.

Role of Trade-offs. In the course of design reasoning, engineers must make trade-offs. To design a car that can protect drivers better in collisions will require consideration of trade-offs between costs and safety. Some designs might require trade-offs between aesthetics and functionality. The completed designed product or system embodies a regime of trade-offs. Contrarily, scientific inquiry has no real parallel to this form of reasoning, allowing for the fact that a decision whether to start or continue a scientific project could be based upon an estimation of the opportunity costs associated with the project.

Role of Failure. As indicated earlier, both scientists and engineers must contend with failure on their respective journeys through the problem space in search of solution. Failure helps both to understand their problem better and to make adjustments in their line of attack. But beyond this commonality, failure has a place in design reasoning that extends beyond that which is shared with inquiry. Poor design can lead to collapse of structures, such as the buckling of bridges under load, the breaking of dams, or to the malfunctioning of equipment. A pacemaker intended to stimulate the heart into rhythmic functioning must work every time. An automated teller machine must pay out only that cash which is requested. Reflecting upon the design of everyday commonplaces (e.g., the aluminum soda can), Petroski (1994) noted that “the concept of failure is central to the design process, and it is by thinking in terms of obviating failure that successful designs are achieved. It has long been practically a truism among practicing engineers that we learn much more from failures than from successes” (p. 1). According to Petroski, it is when engineers fail to tacitly factor failure analysis into their design conceptions that actual failure occurs. Failure considerations, therefore, rise to the level of a design principle. There is no equivalent to this manner of reasoning within scientific inquiry.

Role of Context. Engineering problems are shaped by the strictures imposed by context. The design of heart pacemakers must take into account the environment of the human body within

which they would have to be lodged. Tall structures in earthquake zones must be constructed more dynamically than structures outside of such zones. This sensitivity to particular contexts is not a feature of scientific inquiry. To the contrary, scientific solutions are transcending—they seek generalizable principles.

Practicality Tests. Beyond the critical question “Does it work?” lie other practicality criteria for designs, including whether the design can be manufactured or whether component parts can be assembled. A very functional component design on paper might not be suited for pouring in the foundry. These commercial considerations must be included in the reasoning process of engineers when they design products. Failure to take them into account could be quite costly. Hence, “design for manufacturability” has become a limiting condition on design engineers. Such practicality criteria do not have parallels in scientific inquiry. It is true that scientific processes first honed in laboratories are frequently scaled up for commercial purposes, but by then scientific inquiry merges into engineering. For example, the production of ammonia on a large scale is as much an engineering design problem as it is scientific inquiry.

Implications and Conclusion

The previous discussion has proceeded on the premise that the complementarities we see between science and technology in society can be exploited in schools through the interplay of design and inquiry. First critical steps toward such accommodation in the curriculum have already been taken by the science and technology education communities in the explicit suggestion in both their content standards that science literacy and technological literacy are intertwined. But beyond the respective standards, I have shown here that science and technology educators alike have been experimenting in classrooms, teaching instructional units aimed at helping students to gain science understanding through design and, conversely, that lead them to design through an understanding of science. Clearly, there are prospects here for an accommodation in the curriculum between teachers of the respective subjects. Science teachers and technology education teachers can learn from each other, if only they can find a way to break free from the strictures that have kept them apart in schools, functioning essentially as two separate cultures.

Outside of schools, the scientific and engineering communities are recognizing that they have a stake in children becoming technologically literate (e.g., Bybee, 2000; Institute of Electrical and Electronics Engineers, 2000) and are calling for accommodations between science and technology education in the curriculum. The NSF has in the past decade been actively promoting technology education as a school subject that is complimentary to science by funding significant projects that are so oriented, including *Standards for Technological Literacy* (International Technology Education Association, 2000) and the National Center for Engineering and Technology Education (see www.NCETE.org). The National Academy of Engineering has become an influential advocate for the inclusion of technology education in the curriculum (e.g., Pearson, 2000). Since its discipline embodies science–technology connection, the engineering profession readily sees the prospects of such connection in schools. This article has identified complementarities between inquiry and design that allow for science/technology rapprochement in the curriculum. Implications of such rapprochement are identified next.

Implications

For the interplay between design and inquiry to become the basis of science/technology education accommodation, attendant implications will need to be addressed. Five such

implications are identified here, namely (a) the need to identify best practices or exemplars of such teaching (b) the need for proven curricular and instructional materials to become readily available to school districts and teachers, (c) the need for adjustment of the preservice teacher education curriculum in technology education as well as in science education, (d) the need for professional development of inservice teachers, and (e) the imperative for research.

Need to Identify Best Instructional Practices. If the crossing of borders between inquiry and design is to occur in science and technology education teaching on a consistent basis, there will be a need for identification and dissemination of best classroom practices illustrative of how this is done. As discussed earlier, accounts of teaching aimed at connecting design and inquiry now can be found in the literature of both science and technology education (e.g., Bachtta, 2001; Snetsinger et al., 1999). Some of this work is NSF-funded (e.g., Benenson & Piggott, 2002; Burghardt & Hacker, 2004; Crismond, 2001; Kolodner, 2002). Because NSF-funded projects typically must conform to quality-control regimes and since they typically include highly motivated and exemplary classroom teachers, they can be places where practitioners in the respective fields look for best instructional practice by teachers who have had demonstrable success in crossing inquiry/design borders.

Need for Proven Instructional Materials. Along with the need for exemplary practice in the teaching of design/inquiry to be made widely available is that for appropriate instructional materials that can be used across the grade levels (e.g., Spillane, 1999). Again, the need here will be for materials that have been piloted and field tested, and are reflective of the standards for both subjects.

Need for Adjustment of Preservice Curricula. One important implication of convergence between inquiry and design is that the teacher education curriculum for both technology and science education should address these ideas through course work. A prescription of this order immediately invites the question “What will such insertion in the curriculum replace?” And because such a question is reasonable, one solution might be a compromise approach. Thus, the science teacher education curriculum could include units on design in existing courses that are laboratory based or as a part of science methods. More ideal for science teacher education may be for preservice teachers to take one or more design-based courses that include the solution to open-ended design problems. Most technology teacher education programs require students to take science courses as part of the liberal education requirements. Technology education teachers are not expected to teach science, but in their teacher preparation, they can benefit from science course work that adopts an open-ended inquiry approach. They also could benefit from exposure to units on scientific inquiry in teaching methods courses.

Need for Professional Development. Professional development for inservice teachers may be a more potent way of readying teachers for inquiry/design teaching than preservice education, the teacher education curriculum perhaps being already crowded (see Birman, Desimone, Porter, & Garet, 2000). Because the aim here is to exploit the prospects of border crossings across content lines, one approach that might have promise here could be professional development through learning communities, where teams of technology and science teachers work together in the common search for meaning in their work (Cochran-Smith & Lytle, 1999). Learning communities need chunks of time, and their work tends to be unhurried. In such collaborative communities,

science and technology education can learn from each other. They can engage in rich deliberations about the substance of design and inquiry, and in joint construction of pedagogical knowledge (Spillane, 1999). An important tool here could be videotaping, allowing teams of teachers to review and offer critical feedback to each other about teaching (e.g., Sherin, 2000).

Imperative for Research. The convergence prospects of design and inquiry will warrant a program of research aimed at answering basic questions in realms that could include student learning of science and technology, implementation challenges faced by teachers as they try out new pedagogic approaches, professional development practices that yield best results for teachers and their students, and questions relating to the assessment of learning of science and technology in the context of inquiry/design approaches.

Conclusion—Why an Accommodation between Science and Technology Education?

Given current pressures on schools to improve the academic standing of students and to demonstrate achievement through standardized testing, it may be asked just where would one more curriculum initiative, such as an accommodation between science and technology education, fit? Why should schools bother to effect such accommodation given their multiple other priorities? Indeed, the ideas explored here must take into account attendant implementation difficulties, especially those imposed by the academics-driven school-reform movement. In view of these practical considerations, four kinds of arguments are now offered in response, supporting the main contention of this article that design, because of its conceptual proximity to inquiry, can be a way to bridge science and technology education. They include (a) the imperative of science for *all* students, (b) the prospect of making science careers more appealing by connecting the subject to the designed world, (c) the need for the K–12 curriculum to reflect the societal commonplace of the science–technology interface, and (d) the imperative set forth in the standards for both science and technology education that the designed world be an integral aspect of their content. Each of these arguments is briefly expanded upon next.

The Imperative of Science for all Students. Design has the potential of making science more reachable to a wider array of students, ranging across abilities as well as intelligences (e.g., Gardner, 1999). Many students who might be intimidated by the regular school science curriculum or who view it as the purview of the college bound may see in the problem-based approaches of design that science can be fun and is a subject worth pursuing. Mousetrap vehicles, solar-powered devices, rocketry, or the design of structures such as bridges are exciting ways of introducing scientific principles to children. Such approaches stimulate interest in a wider pool of children, many who may otherwise turn away from science. The act of designing introduces problems and challenges in the classroom that can be resolved by knowledge of science. Students whose desire is to design the most energy efficient device will be more likely than otherwise to seek out the needed scientific knowledge.

Making Science Careers More Appealing by Connecting the Subject to the Designed World. It is possible that many children will begin to consider science careers when, through design, they see the science in everyday technological commonplaces (e.g., Benenson, 2001). The designed world of engineers and other technologists must conform to scientific principles and laws. Automobiles, refrigerators, television sets, shopping bags, and other everyday artifacts must obey the laws of physics. The revelation that science is all around them, embodied in

commonplaces, shows to children that their conceptions of what science careers entail might need to be expanded. They begin to see that science is not exclusive knowledge used by scientists only; instead, they learn that science is used by people across a broad spectrum of careers. That revelation makes it easier for children to see science as being reachable, and can make a difference in their achievement in science.

Reflecting the Societal Commonplace of the Science–Technology Interface in the K–12 Curriculum. As noted at the beginning of this article, science and technology are often inseparable in society, evidenced in high-profile projects such as sending astronauts into space. Scientists, engineers, and technicians routinely work collaboratively on projects, whether in aircraft design or on construction projects such as dams, tunnels, or bridges. In chemical plants, engineers design reactors in accordance with specifications produced by chemists. For example, they must take the amount of heat likely to be generated by a particular chemical reaction into account in determining wall thickness and other critical reactor dimensions in their designs. Here, engineers and chemists must collaborate. The design approach in the K–12 curriculum offers children opportunities to enact in the classroom the commonplace collaboration between professionals of these disciplines in the real world. The result of such collaboration is that students begin to see connections in the curriculum that are not otherwise possible. Such connections make the curriculum more authentic and more relevant. The result is increased student interest and, arguably, increased prospects for learning.

The Standards Imperative. As indicated earlier in this article, the published standards for both science and technology education include design as critical content. Science teachers do not have a tradition of teaching three-dimensional aspects of design or working in contexts such as manufacturing, power and energy, or construction. Technology education teachers, on the other hand, are steeped in such teaching, but they typically do not have the requisite scientific knowledge that undergirds design. Collaboration as proposed here, makes design the joint responsibility of two subject areas, avoiding duplication in the curriculum. Additionally, it draws on the strengths of the two kinds of teachers. For example, in the design of a supermileage vehicle or a bridge where technology education teachers can provide expertise in aspects of the design involving brainstorming and prototyping, science teachers can provide the underpinning scientific concepts and principles.

Without collaboration as proposed here, there is a real chance that science teachers may simply ignore the design aspect of their subject's content, thus depriving children of real opportunities to situate their learning in applied contexts. Further, absent collaboration, many technology education teachers may continue to teach design but exclude its underpinning scientific aspects because such content is not within their repertoire. When the two types of teachers collaborate, these problems disappear or are substantially eliminated.

Ultimately, a design approach offers great prospects for student learning by connecting science to technological contexts. The approach supports the mutually supportive goals of scientific and technological literacy. In time, best practices for teaching design as content for both science as well as technology education will evolve as the two communities of teachers learn how to work with each other and to complement each other's expertise.

There has been lament that young people are not opting for scientific and engineering careers in proportion to societal need. Spurred on by the NSF, important national bodies in engineering and science (e.g., Institute of Electrical and Electronics Engineers, 2000; Pearson, 2002) have

been suggesting that new pedagogies are called for in the K–12 curriculum that are integrative in approach, showing fluidity between engineering and science. In this conversation about what schools can do to turn around the seeming disinterest in scientific and engineering careers, the goal of technological literacy has risen to prominence and is seen as complementary to that of scientific literacy (e.g., Bybee, 2000). Because of its conceptual proximity to inquiry and its standing as both science and technology, design has been offered here as a means of effecting synthesis in the curriculum.

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