

The Theoretical and Empirical Basis for Design-Based Science Instruction for Children

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### *Section 1. Introduction and Key Terms*

A recent trend in primary and middle school education has been to incorporate into science instruction the activities and vocabulary of the analytical design professions, such as architecture and engineering (Kolodner, 2006; Krajcik & Blumenfeld, 2006; Penner, Giles, Lehrer, & Schauble, 1998; Roth, 1996; Sadler, Coyle, & Schwartz, 2000). For many primary and middle level educators, the use of design in classroom instruction makes intuitive sense, since children can so frequently be found to be designing and building solutions to their own problems, such as when they construct objects and structures for play (Baynes, 1994). Some educators even suggest that it is more natural for children to design and build than it is for them to investigate and experiment (Schauble, Kloper, & Raghavan, 1991; Schauble, Glaser, Duschl, Schutze, & John, 1995).

Despite our intuition about children's natural proclivity for design, the field of research on design-based science instruction remains relatively under-developed compared to the large number of studies on inquiry-based approaches. As a result, educators have little comprehensive information on the effectiveness of teaching science through design activities. Further, curriculum developers lack a description of the strengths and weaknesses of current instructional materials intended to help students learn science through design activities.

Consequently, my primary goal in this paper is to report comprehensively on the current state of design-based science instruction for children. I will review and synthesize theoretical and empirical literature in an attempt to assist educators, researchers, and developers in their efforts to define effective approaches to design-based science instruction for upper elementary students. My focus is on upper elementary-school students (roughly eight- to eleven-year-olds) because due to their young age, these students are most likely to be influenced by novel instructional

activities such as design-based science.

To generate a report about the current state of design-based science for children, I will review previous studies on elementary and middle grade (K-8) design-based science instruction. I include middle school material in my review because the literature on elementary-school children's designing is scarce, and middle school instruction can often be adapted for the upper elementary grades. I will inform my review of empirical studies with relevant perspectives from the fields of situated cognition, distributed cognition, and engineering design theory.

Because many of the terms related to design activities have multiple meanings both in and out of the academic arena, I begin with some definitions of key terminology specific to this review paper. Then I present the reader with a roadmap for the paper.

*Design.* Design is an ambiguous and ubiquitous term, as it refers broadly to *any human activity aimed consciously at either synthesizing a product that will solve an open-ended and ill-structured problem, or specifying plans from which the product can be realized* (Dym, 1994; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Simon, 1996). Design entails effecting change in the material world and changing a situation from the way it is to the way one wishes it to be (Simon, 1996). Humans engage in design to solve many kinds of problems in domains as varied as organizational design, fashion design, interior design, artistic design, graphic design, and architectural design. Engineering design is one of many types of design activities (Dym, 1994).

*Engineering design.* Because it is unique to one domain of practice, *engineering design* can be defined with more precision than design in general. It is *the organized development and testing, through the use of mathematical and scientific knowledge and models, of specifications for artifacts that perform a desired function without violating known constraints* (Davis &

Gibbin, 2002; Dym & Little, 2004). By mathematical and scientific models, I mean representations of natural and man-made processes through equations, graphs, algorithms, and other representational systems. By artifacts, I mean human-made objects or devices, which may be three-dimensional, such as vehicles and water filters, two-dimensional, such as drawings and printed sets of instructions, or digital, such as computer software and computerized models. Though the word artifact is also occasionally used to describe internal cognitive structures, I use it only to refer to external creations.

*Engineering.* Given the above definition of engineering design, *engineering* can be described as *a complex enterprise whose goal is to apply creativity and knowledge of mathematics and science to make available solutions to society's needs and wants* (Wulf, 1998). Engineering *design* is just one activity – though a central activity – within the multifarious enterprise of engineering, which also includes activities of failure analysis, economics, aesthetics, communications, and quality control (Petroski, 1996). Engineering, broadly conceived as human problem-solving, has been practiced throughout history, but in recent centuries it has been formalized into professions and academic disciplines highly reliant on mathematical analysis and scientific understanding (Petroski, 1996). Modern professional engineering firms work to make problem-solving products, systems, and analyses available to the public.

*Technology.* *Technology* consists of *the artifacts and systems that result from the engineering enterprise* (Wulf, 1998). Technologies are the products of consumer-driven engineering as well as the outcomes of interplay between the science and engineering disciplines (Benenson, 2001). For example, engineers design new measurement instruments that allow scientists to carry out novel types of investigation, and scientists make discoveries about the natural world that allow engineers to take advantage of new materials and models. In this paper, I

use the terms *technological design*, *engineering design*, and *design* interchangeably to refer to activities in which children construct solutions to problems similar to those solved by professional engineers.

*Design artifact.* The design solutions created by children typically are tangible and three-dimensional. I refer to these results of the children's engineering design as "design artifacts." More precisely, a *design artifact* is a *tangible, student-constructed product that is designed and created to perform a specific function or solve a specific problem* (Dym, 1994; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Roth, 1996).

The main body of this paper begins in the second section by painting a brief picture of the educational landscape in which design-based science instruction has taken shape. The third section, on relevant theoretical perspectives, presents some main ideas from the situated cognition and distributed cognition theoretical frameworks, and suggests some possible implications for the teaching of science through design activities. Next, the fourth section, on empirical studies, reviews five representative approaches to teaching science through design in elementary and middle school classrooms. The fifth section synthesizes lessons from these empirical approaches with ideas from the cognitive theoretical perspectives presented in the third section. Some findings from research on the practice of engineering design are incorporated into this synthesis. Finally, the concluding section summarizes the contributions for this paper and suggests a framework for future research. The guiding question for this review is: to what extent is there a theoretical and empirical basis for teaching elementary science concepts through engineering design activities?

## *Section 2. The Educational Landscape of Design-Based Science Instruction*

### *The National Context: United States Science Education Reform Efforts*

Before I describe the emergence of design activities in primary science classrooms, it is helpful to situate them within the general atmosphere of primary science education reform efforts in the United States. When the National Science Teachers Association (NSTA) and the National Research Council (NRC) introduced the first *National Science Education Standards* (NSES) for grades K through 12 in 1996, they included *scientific inquiry* as a major theme of their recommendations (NRC, 1996). Their decision to define school science as an inquiry process followed a long history of efforts, first at the college and secondary levels and then at the elementary level, to include inquiry as both a learning goal and a teaching method for school science. As early as 1920, the National Education Association (NEA) insisted in a major report that science was more a process than a collection of facts, and that one major goal of secondary science teaching should be to develop students' abilities to observe, measure, classify, and reason from evidence (NEA, 1920, cited in DeBoer, 1991). In spite of this and similar reports, surveys of actual secondary science classrooms around the middle of the century indicated that most science teaching still consisted of traditional lectures and memorization assignments (DeBoer, 1991). However, the international political climate after World War II and the launch of *Sputnik* in 1957 almost instantly sparked a movement that would effect real change in science education.

*Reform in the 1960s.* The Soviet Union's launch of *Sputnik* spurred American scientists and science educators into action. In 1959, the National Academy of Sciences convened a ten-day meeting called the Woods Hole Conference, at which 35 invited scientists and educators collaborated to offer guidance on future developments in U.S. science and mathematics teaching. Jerome Bruner's (1960) report on the conference emphasized teaching the organized structure of



scientific disciplines as well as the modes of inquiry and the attitudes of scientific investigation. Just after the publication of Bruner's report, educational theorist Joseph Schwab called for a fundamental change in teaching science, toward an approach that presented science not as a static body of knowledge but as a fluid set of principles that could be revised whenever necessary, through the inquiry of scientists (DeBoer, 1991). Schwab's main message was to teach science as "enquiry" (1962, cited in DeBoer, 1991), and he contributed a set of "Invitations to Enquiry" for a new biology course (Biological Sciences Curriculum Study, 1963a). One of his central ideas was that teachers should employ multiple modes of inquiry instruction and support all of them with vigorous class discussions. In the most direct mode of inquiry instruction, textbooks or lab manuals specify the questions and the methods that enable students to discover certain scientific principles; in the least direct mode of instruction, students propose their own questions and methods to investigate any phenomenon of interest (DeBoer, 1991; NRC, 2000).

*National Science Foundation curriculum development.* Concurrently with Schwab's efforts and the Woods Hole Conference, the National Science Foundation (NSF) began sponsoring committees of college science professors and K-12 educators to develop new curriculum for the various science disciplines. The original NSF-funded project, spearheaded by MIT physicist Jerold Zacharias, was the Physical Science Study Committee (1960). Other high school science curriculum projects included the Biological Sciences Curriculum Study (1963b), the Chemical Education Material Study (1963), and the Earth Science Curriculum Project (1967). Three NSF-sponsored committees focused on elementary science education, and they produced three new courses, the *Elementary Science Study* (Education Development Center, 1969), the *Science Curriculum Improvement Study* (1970), and *Science – A Process Approach* (American Association for the Advancement of Science, 1967). Each of these courses, with

varying degrees of curricular structure, deemphasizes science facts and encourages children's hands-on participation in the processes of science. In 1977, 32% of the elementary schools included in a nationwide survey were using one of the three NSF-sponsored science programs (DeBoer, 1991). Some elementary educators found great success with these programs, but others declined to adopt them, citing concerns about obtaining materials, maintaining classroom discipline, neglecting important science facts, and overcoming the difficulty most students initially experienced with inquiry learning. Another obstacle to adoption of the new programs was standardized testing, which led school districts to continue to adopt more traditional, fact-based science textbooks (DeBoer, 1991).

Although the NSF-supported elementary science materials faced criticism, and their use did not become as widespread as had been hoped, they exerted substantial influence on the thinking of science educators:

If a single word had to be chosen to describe the goals of science educators during the 30-year period that began in the late 1950s, it would have to be *inquiry*. Inquiry teaching was intimately associated with the NSF curriculum projects and was viewed long afterwards as an educational ideal worth striving for. (DeBoer, 1991, p. 207)

Indeed, by the time the NSES were published in 1996, the changes of the 1950s, 1960s, and 1970s had so successfully disseminated ideas about inquiry that the NRC and NSTA readily committed to lifting up both *inquiry teaching* and *learning about inquiry* as standards for the entire nation (NRC, 2000).

*Inquiry after the National Science Education Standards*. For each age range addressed by the NSES, the NRC and NSTA identify specific "Science as Inquiry" standards, spelling out the understandings and abilities that teachers and students should have regarding scientific inquiry (NRC, 1996, p. 105). They broadly define *inquiry* as the set of ways of thinking and acting that includes "asking questions, planning and conducting investigations, using appropriate tools and

techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments” (NRC, 1996, p. 105).

Recognizing that broad definitions and standards do not alone create a successful reform effort, the NRC published an addendum to the standards entitled *Inquiry and the National Science Education Standards* (NRC, 2000). This addendum presents several extended examples of inquiry-based science instruction in K-12 classrooms. Each showcases five essential features of classroom inquiry: engaging students with scientifically oriented questions, giving priority to evidence, formulating explanations from evidence, evaluating explanations in light of alternative explanations, and communicating and justifying proposed explanations (NRC, 2000).

As the NSES and its addendum were being prepared, the NSF was in the meantime funding the development of several explicitly inquiry-based primary science curricula. This was essentially a second generation of NSF-funded elementary science curriculum projects. Three of these curricula, *Insights* (Education Development Center, 1997), *Science and Technology for Children* (National Science Resources Center, 1997), and *Full Option Science System* (Lawrence Hall of Science, 2000), were first published in the late 1990s and are widely used in elementary schools today (G.M. Barnett, personal communication, January 2007).

### *The International Context: European and Australian Approaches to Design and Technology Education for Children*

In the 1980s and 1990s, as science educators in the U.S. were working to incorporate the inquiry practices of real-world *science* into the national standards, western European and Australian educators were striving to incorporate concepts and ways of thinking from the *design*

*and technological* professions (including engineering and architecture) into primary education. These efforts have been described by Layton (1993) as the “vocationalising” of education, a trend toward creating learning opportunities oriented to the world of work, industry, and commerce. This movement was partially based on economic considerations and social equity issues, but it was also spurred by the perception that society was losing its ability to control technology. People began to view technology-oriented education as a means to ensure society’s control over technology (Layton, 1993).

*United Kingdom.* Technology has been one of the ten main required subjects in the United Kingdom since the 1988 Education Reform Act, which established a mandatory national curriculum of math, English, science, history, geography, music, art, physical education, foreign language, and technology. Technology education had existed in schools in the U.K. before 1988, but only in a broad, non-nationalized assortment of courses. In the 1960s, some schools offered a version of technology education that focused on engineering challenges, but this program failed to take hold because of a contentious debate over whether scientific concepts or craft skills should form the foundation of students’ work (Layton, 1993). In the 1980s, the Science, Technology, and Society (STS) movement gained prominence in the U.K., and lessons emphasizing the interplay of science, technology, and society began appearing in classrooms. One drawback of these instructional activities was that they positioned technology only as an auxiliary application of science (Layton, 1993). Another movement of the 1980s, called Craft, Design, and Technology (CDT), challenged this parochial view by bringing technology to the forefront of instructional activities. Many schools in the U.K. offered CDT courses, but they encompassed so many different topics – including sewing, woodworking, computer use, and jewelry-making – that no school exam could cover them all, and no national CDT curriculum

could be written. However, the summative effect of these courses was powerful enough that by the end of the 1980s, the U.K. Association for Science Education had issued a policy stating that technological education should be part of every student's liberal education (Layton, 1993).

Eventually, design processes became a major component of technology courses in the U.K., and by the time the National Curriculum was created, consensus had formed around the Design and Technology approach to technology education. In contrast to the STS and CDT approaches, the current Design and Technology approach broadly defines technology as any artifact, system, or environment that result from a design process. The six major learning goals of the national Design and Technology curriculum are (1) developing, planning, and communicating ideas; (2) effectively using tools, equipment, materials, and components to produce products; (3) evaluating processes and products, (4) understanding materials and components; (5) understanding systems and control; and (6) understanding of structures.

*The Netherlands, Finland, and Australia.* Other countries that incorporated design and technology education into their pre-university system in the 1980s and 1990s include the Netherlands, Finland, and Australia. In the 1980s, the Netherlands' approach placed a strong emphasis on craftsmanship skills (Layton, 1993). Under this approach, students typically used already existing design plans to create items within the woodworking, metalworking, and textile trades. The learning goal was to gain knowledge of the materials and practices required for the creation of quality products (Raizen, 1997). In contrast to this crafts-based approach, the technology education approach implemented in Finland in the 1980s emphasized high-tech processes of automation and computer-controlled production (Layton, 1993). The goal was for students to learn how to use high-tech equipment and software; as a result, the cognitive aspects of designing were not stressed. Australia currently offers yet another version of technology

education, called Technology & Enterprise (Western Australia Curriculum Council, 1998). In the state curriculum of Western Australia, Technology & Enterprise is one of the major academic disciplines. As students progress through the grade levels, they are expected to master the “technology process,” whose goal is to “create or modify products, processes, systems, services or environments to meet human needs and realise opportunities,” and whose key practices are investigating, devising, producing, and evaluating (Western Australia Curriculum Council, 1998).

### *Efforts to Include Design, Technology, and Engineering in U.S. Primary Education*

In the U.S., despite a 40-year-old science education reform movement, efforts to incorporate design and technology into primary education did not receive national attention until the 1990s. In that decade, U.S. educational policymakers began asserting that awareness of and knowledge about design, technology, and engineering (also referred to as “The Designed World”; see American Association for the Advancement of Science, 1993) are crucial to students’ ability to navigate our technology-dependent society. Several national committees called for the integration of technology, technological design, or engineering into elementary curricula (International Technology Education Association, 1996). This effort, often called the technological literacy movement, achieved national visibility in 1996, when the International Technology Education Association (ITEA) and the NSF published the *Technology for All Americans Project, A Rationale for the Study of Technology*. Specific recommendations about the content of technology education were made in 2000, when the NRC joined with the ITEA to establish national standards for technological literacy (ITEA, 2000). Two years later, the NRC converted to the use of the word “engineering” and published two studies that make the case for

pre-college engineering education (Davis & Gibbin, 2002; Pearson & Young, 2002).

Although these publications make persuasive arguments, they have not succeeded in changing the average American elementary school classroom. In all regions of the country, there are individual teachers who embrace the instructional richness of the design process (Davis, Hawley, McMullan, & Spilka, 1997). However, at the institutional level, primary level and middle level instructional programs involving engineering design are not well supported. One explanation for the lack of widespread acceptance of engineering or technological design curricula is that educators lack comprehensive data on either their learning impact or their feasibility of implementation. Furthermore, the body of knowledge on *how* students learn about technology and engineering is small (AAAS, 1993). Despite all the educational policy initiatives, there are few published studies of how pre-college students – especially elementary students – learn about engineering or technological design.

An even more compelling explanation for the failure of engineering design to become a prevalent activity in elementary school is that U.S. educators perceive it as yet another new, stand-alone school subject. Even in the state of Massachusetts, where questions about the engineering design process are now included in high-stakes fifth-grade statewide assessments, most teachers are not addressing the subject in their classrooms (Dubina, personal communication, November 2006). They justify their avoidance of engineering design by citing an absence of curricular materials, lack of professional development, and no extra time allotted for a new academic discipline (Dubina, personal communication, November 2006). Despite concerted efforts by design professionals and educational policymakers, most primary educators in the U.S. still perceive engineering design as irrelevant to their students' intellectual development.

*Positioning Design as a Type of Inquiry-Based Science*

However, design tasks for children have not disappeared entirely from U.S. education reform movements. Instead, efforts to engage children in design activities have intersected productively with the continuing efforts to achieve inquiry-based science education. At this intersection, the science education research community has envisioned a new role for design in the elementary school classroom. Design has been found to require the same core thinking strategies as scientific inquiry, namely, analysis, synthesis, and evaluation (Crismond, 2001). Rather than comprising an additional academic discipline, engineering or technological design tasks have been reconceived as *contexts* or *supports* for students' scientific inquiry (Baumgartner, 1999; Lewis, 2006; Penner et al., 1998).

*Contrasting inquiry and design.* However, as professional and cultural activities, design and inquiry have some fundamental differences, and it is important to account for this tension before considering how the two activities can support each other. Design and inquiry activities differ along at least five major characteristics, which are summarized in Table 1. First, design and inquiry have different driving *purposes*. When engineers engage in design, their basic purpose is to create a product that will solve an open-ended problem (Simon, 1996), whereas when scientists engage in inquiry, their essential goal is to develop new knowledge about a particular phenomenon of interest (American Association for the Advancement of Science, 1993; Kuhn, 1996/1962). Second, although designers and inquirers make use of many of the same skills and practices, they *emphasize different processes* as they work to achieve their goals. Designers often emphasize the processes of enumerating a problem's constraints, brainstorming possible solutions, testing prototypes of selected solutions, and reiterating through previous steps (Davis, Hawley, McMullan, & Spilka, 1997). Inquirers, on the other hand, focus on the processes



of refining the question, making and analyzing observations, generating explanations, and testing the applicability of explanations to further observations (National Research Council, 1996).

Third, design and inquiry feature different *outcome spaces*, or sets of possible results (Fortus, 2003). Design activities have an infinite number of possible outcomes, since any problem can be solved in multiple ways. In contrast, inquiry activities typically strive to generate consensus around one single explanation. Fourth, design and inquiry outcomes have different *evaluation criteria*. Design outcomes are evaluated according to whether they solve the problem or accomplish the task for the intended user, while inquiry outcomes are evaluated according to whether the explanation is accepted by peers and found to remain true for new cases of the phenomenon under investigation (Kuhn, 1996/1962). Fifth, *prior science knowledge* plays different roles in helping designers and inquirers reach acceptable outcomes (Layton, 1993). Designers use prior science knowledge as a background resource for informing design decisions such as material selection, structural layout, and appropriate modeling technique. Inquirers apply prior science knowledge differently; they use it to create an initial explanation or hypothesis, to make sense of observations, and to choose proper testing instruments.

The real-world activities of design and inquiry have been adopted for use in the science classroom setting, and in this environment two additional differences emerge. First, the two activities provide different motivation for the acquisition of new knowledge. During design activities, students are motivated to acquire new knowledge by a practical need to create a successful product (Fortus, 2003). During inquiry activities, students are often motivated by more extrinsic factors such as teacher evaluations and coming to the “correct” conclusion (Fortus, 2003). The second classroom-specific difference between design and inquiry involves the role played by student-constructed artifacts. When students engage in design tasks,

completed artifacts serve as evidence that the goal of the activity has been achieved. In inquiry activities, student-constructed artifacts play more secondary roles, such as facilitating the collection of data or displaying student ideas.

*Table 1. Differentiating design and inquiry as professional and classroom activities*

	Real-world design	Real-world inquiry
Purpose	To create a product that will solve an open-ended problem	To develop new knowledge about a particular phenomenon of interest
Key Processes	Identify need, <i>identify constraints</i> , research, <i>brainstorm</i> , design, build, test, share, repeat	Identify question, hypothesize, plan, collect info, explain, test explanation, repeat
Outcome Space	Infinite solutions, no one correct answer	Answers that are accepted by peers
Evaluation of Outcome	Whether it accomplishes task for intended user	Whether peers accept explanation; whether explanation holds in other similar cases
Role of Prior Science Knowledge	Resource for material selection, structural design, testing methods	Resource for experiment design, explanation generation, testing instruments

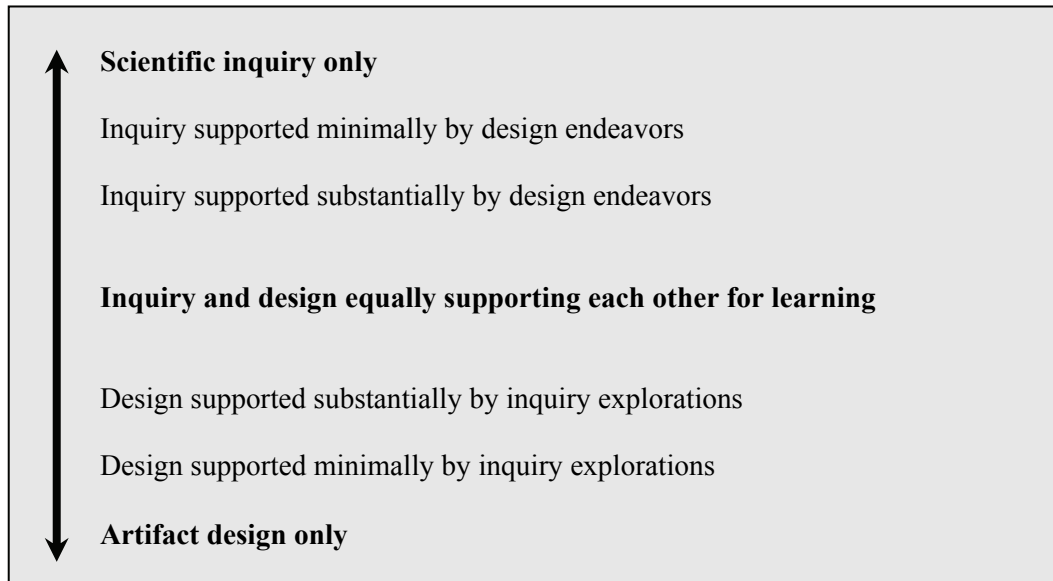
  

	Classroom design	Classroom inquiry
Motivators for knowledge acquisition	Move forward in design; correct design failures	Answer question; receive positive evaluation from teacher
Role of Artifact	Solution to problem, object that achieves goal of activity	Motivator, test-bed, measuring instrument, display of ideas

*Positioning classroom design and inquiry along a continuum.* Although we can describe design and inquiry as fundamentally different activities, in the reality of a classroom setting, it is often difficult to differentiate one activity from the other. For example, if children in a science classroom are creating cardboard models of bean plants, are they participating in the construction phase of a design project, or are they preparing to share their explanations at the end of an inquiry investigation? The answer to this question depends on the teacher's instructional goals and the larger context for the activity. In the classroom setting, the line between design and

inquiry is often blurry, and the two activities may not be as distinct as their definitions suggest. In the classroom, almost all activities involve both the constructing of some sort of artifact and the posing of some kind of query. Students are always creating products *and* answering questions about the world, to differing degrees at different times.

Rather than insisting on a dichotomy between these two omnipresent classroom activities, we can describe the relationship between classroom inquiry and classroom design as a *continuum*. At one end of this design/inquiry continuum, the *inquiry only* end, we place inquiry-based science class activities that involve no artifact design. For example, an exploration of grass plants' growing patterns would be located at the inquiry-only end of the continuum. At the other end of the continuum, we place design-based science class activities that involve no inquiry; this is the *design only* end. A session in which children build straw-and-tape bridges without investigating the underlying patterns of failure and success would be classified as design-only. In the middle of the continuum, we place several other categories of science class activities: those in which inquiry is the main goal and is partially supported by design endeavors, those in which design and inquiry support each other equally, and those in which design is the main goal and is partially supported by inquiry explorations. Figure 1 depicts the entire continuum. Neither end of the continuum is necessarily better or worse than the other; the continuum is a descriptive tool rather than a value-laden prescriptive tool.



*Figure 1. The design/inquiry continuum for constructivist science classrooms*

Let us zoom in on the middle of the continuum, where inquiry and design support each other equally. To illustrate how design and inquiry can support each other, I will match the features of classroom inquiry with the components of children's engineering design. In design activities, children attempt to solve a problem by planning a possible solution, building and testing prototypes, determining if and how the prototypes function, and communicating the best design solution (Kolodner, 2006). In inquiry activities, children try to answer a question by planning an investigation, gathering data, constructing explanations from this evidence, and communicating the best explanation (NRC, 2000). Table 2 shows how these five aspects of elementary school scientific inquiry correspond with the major aspects of elementary engineering design. These correspondences show how design activities can support children's development of inquiry abilities. First, design problems can be translated into questions of scientific inquiry (e.g., How can I design something that...?). Then, the activity of planning

design solutions can help students learn to plan scientific investigations. The process of building and testing prototypes can be construed as another sort of scientific data gathering. The task of analyzing prototypes can function as an opportunity to practice creating scientific explanations. And finally, the activity of sharing final design solutions can be similar to communicating scientific explanations.

*Table 2. Corresponding aspects of elementary-school inquiry and design*

	<b>Abilities necessary to do inquiry in grades K-4 (NRC, 2000)</b>	<b>Corresponding aspects of children's engineering design (adapted from Kolodner, 2006)</b>
1	Identifying a question about an object, event, or organism in the world	Identifying a specific need that can be considered a design problem
2	Planning an investigation	Planning a design solution
3	Gathering data	Building and testing prototypes of design solution
4	Constructing explanations from evidence	Explaining why prototypes function or do not function
5	Communicating explanations that answer the original question	Communicating and justifying the final design solution

*Design-based science.* Educators and researchers who use or study *design-based science* instruction offer an alternative vision of how design and inquiry can support each other in the science classroom (for example, see Baumgartner, 1999; Fortus et al., 2004; Kolodner, 2006). For them, using design as a support for scientific inquiry means posing to students a design problem whose solution requires understanding of some particular science content. In a design-based science activity, students engage in scientific investigations to deepen their understanding of aspects of the problem or of the potential solutions, and thus to enable themselves to solve the problem or to improve upon a previous solution. For example, to tackle the design challenge of constructing a musical instrument, students must understand the relationship between an object's physical qualities and the sound it produces. The design of musical instruments may provide a context, and thus a support, for inquiry into the physics of sound. According to this vision of classroom design, design-based science activities act as a vehicle for inquiry-based science

instruction. If children's engineering design is conducted according to this vision, then science inquiry, and therefore science learning, should occur.

In addition to supporting scientific inquiry during the instructional activities themselves, design endeavors may also increase the likelihood that science learning is retained over both short-term and long-term time periods. Immediate retention may be improved because student would be able to draw upon their memories of their design artifacts as well as their memories of classroom discourse and written work (Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, et al., 2003; Roth, 2001). Long-term retention may be enhanced because over time, repeated exposure to design challenges may change the way that students approach science questions. They may build up a repertoire of design *cases* and begin to use these cases, as well as hypothetical design situations, as tools for finding answers to questions about science phenomena (Kolodner, 2006). This type of case-based reasoning has been shown to improve conceptual understanding (Kolodner et al., 2003). Most studies of design-based science use only proximal measures of student learning; that is, they assess students only immediately after the instruction. Distal assessments, which would take place several weeks or months later, may lend support to the argument that because design-based science units promote case-based reasoning, they also promote conceptual change over long time periods.

*Limitations of design as a support for inquiry.* Of course, not all design problems are well suited for supporting science learning; they do not all prompt scientific inquiry or even require science content knowledge. Because of the myriad uses of the word *design*, it is important to reiterate that in discussing design-based science, I am referring to technological or engineering design problems, rather than to artists' or craftsmen's design tasks. It is also important to acknowledge that even some technological design problems can be adequately solved through

trial-and-error methods that require no underlying conceptual science knowledge (Roth, 1996). Furthermore, classroom design activities that fall on the “design only” end of the inquiry-design continuum are not intended to support the learning of specific science concepts, and therefore they (understandably) omit the fourth aspect of Table 2. When participating in these activities, students are not required to explain why their prototype works (for example, see Benenson, 2001). When this *explanation* element of engineering design is omitted, science learning is not sufficiently supported (Baumgartner, 1999; Kolodner, 2006). This outcome may be acceptable when conceptual change in science is not the stated goal of the instruction. Instead, development of designerly skills or technological literacy may be the stated learning objectives. However, in this paper, my aim is to identify the characteristics and instructional contexts that best enable technological design problems to support science learning. In other words, I am most interested in instructional activities that fall within the middle portion of the design/inquiry continuum.

In the preceding paragraphs, I have laid out the landscape of educational reform efforts in which current attempts at implementing design-based science are situated. I have also contrasted and then synthesized the characteristics of artifact design and scientific inquiry. However, the fact that design and inquiry endeavors have many corresponding aspects does not by itself prove that design is a productive context for children’s scientific inquiry. We might ask: does cognitive theory give us reason to conclude that engineering design tasks may truly foster science learning? To explore this question, I move forward to review the theoretical perspectives on learning and cognition that are relevant to studies of design-based science instruction.

### *Section 3. Theoretical Perspectives Relevant to Studies of Design-Based Science Instruction*

Two major theoretical perspectives on learning contextualize cognition within a social and material world. Both perspectives lend support to the argument that engineering design tasks can be a vehicle for science learning. First, *situated* cognition theory leads to the suggestion that engineering design may be an authentic cultural activity that situates the learning of, and gives everyday meaning to, science concepts. Second, *distributed* cognition theory suggests that engineering design may spread the cognitive load of achieving scientific understanding among design products (artifacts), design teammates (classmates), and design coaches (teachers), thereby augmenting the individual student's capacity for science learning. In this section of the paper, I explain the situated cognition and distributed cognition perspectives in more detail, and I elaborate on their relevance to the study of design-based science learning.

#### *Situated Cognition Theory*

Engineering design is a social and material practice in which members of society regularly engage. Thus, it is a *sociocultural* activity. In particular, engineering design is a sociocultural activity that involves the application and synthesis of scientific knowledge. Consequently, described in the terminology of situated cognition theory, children's design activities may function to situate – and thus make meaningful – cognitive efforts related to science.

*Vygotsky's socioculturally situated learning.* To examine in depth what situated cognition theory might tell us about engineering and science learning, it is important to go back to the origins of the theory, in the work on sociocultural learning by Vygotsky (1962). One of his main contributions was the proposal that although academic or scientific concepts are distinct from



children's spontaneous everyday concepts, these two kinds of ideas depend on each other and develop toward each other from complementary sources. One source of concept development is children's everyday interactions with the material world. Based on these interactions, children form spontaneous concepts about objects and phenomena in the world around them. Initially, these everyday concepts are non-definable and non-operational (Vygotsky, 1962). Children achieve awareness of the object or phenomenon to which a concept refers, but they are not immediately able to define the concept in words or operate with it at will. In other words, everyday concept acquisition does not entail conscious thinking about the object or phenomenon named by the concept. This consciousness gradually develops with the child's expanding experiences in the world.

As the child accumulates these experiences, the other source of concept development identified by Vygotsky begins to play a role. This other source consists of verbal definitions externally imposed by other people. These definitions function as the starting point for children's academic or "scientific" concepts (Vygotsky, 1962). For a child to obtain full consciousness of thought about an object or phenomenon, the everyday concept must intersect with a related academic concept. Put another way, for a child to absorb a verbal definition and transform it into a formal academic concept, the child must possess a related everyday concept that has reached a certain level operations.

Vygotsky's proposal that everyday and academic concepts develop toward each other to enable fully operational thinking has intriguing implications for design-based science instruction. Design activities present children with opportunities for novel and interesting interactions with the material world. The construction and manipulation of tangible artifacts that occur during design activities may thus fuel the development of spontaneous concepts. These new concepts,

based in the children's interactions with their design artifacts, may then lend meaning to scientific concepts imposed by teachers or classmates.

For example, consider a group of elementary school students attempting to construct interlocking block towers that will support a heavy book. As the students build tower after tower in an effort to create the tallest tower that can remain upright, they notice that the towers with extra blocks near the bottom are able to reach higher heights before a book causes them to topple. The students' experiences with the tower materials leads them to the discovery that dedicating a few extra blocks to the bottom of the tower is helpful in the long run. Consequently, when these students' teacher later introduces the notion of structural *stability*, the students absorb the concept because they have already acquired, and have even begun to operationalize, an everyday version of it.

*Meaningful understanding through situated learning.* Following Vygotsky, contemporary scholars of situated cognition also help us think about the role that engineering design activities might play in science learning. Brown, Collins, and Duguid (1989), along with Lave and Wenger (1991) and Rogoff (1991), were some of the first theorists to write about situated cognition in the Vygotskian tradition, and Roth (1996) has applied situated cognition specifically to the realm of primary science classrooms. These scholars' view of cognition, which is consistent with Vygotsky's insistence on the sociocultural nature of learning, asserts that *an individual's cognition is embedded in and inseparable from the individual's situation and activity in a community of practice* (Brown et al., 1989). In other words, *concepts* are always enmeshed with *culture* and *activity*, and the meaningfulness of learning is constrained by all three conditions.

Brown et al. (1989) follow Vygotsky in arguing that abstract concepts are not useful unless they are situated in continued, evolving sociocultural activity. Conceptual knowledge is

like a *tool* that is helpful only when introduced in situations where it can perform some real function. A tool without a purpose simply sits in the tool box. As an example, Brown et al. point out the poor word usage that results when children are taught vocabulary through dictionary reading. Based on dictionary experiences, children can define many words, but they cannot combine them into a meaningful sentence. Indeed, “learning from dictionaries, like any method that tries to teach abstract concepts independently of authentic situations, overlooks the way understanding is developed through continued, situated use” (Brown, Collins, & Duguid, 1989, p. 33). The mere acquisition of tools does not imbue them with relevance or meaning.

Applied to science instruction, this argument predicts the ineffectiveness of teaching abstract science concepts without a situation in which they are used in real life. However, it is certainly possible to present conceptual tools within authentic situations. In a school science classroom, science concepts may be the tools, and engineering design activities may be one of their worlds of use. Students who use science concepts actively in the creation of engineering solutions might build a richer understanding of both the science concepts themselves and of the technological world that science concepts have helped to create.

My observations of children’s learning about sound help to illustrate this idea. Many children’s initial exposure to scientific discourse about sound occurs when an adult introduces the concept of *vibration* and announces that all sound is made from vibrations. As a result, quite a few children readily use the term *vibrations* to answer my questions about how sounds are created. However, I observe that they cannot explain what *vibration* means, nor can they identify what object is vibrating. Fortunately, this state of affairs changes after the children have an opportunity to construct guitars, drums, and maracas out of small building toys, rubber bands, and balloons. These young engineers discover that to cause their percussion instruments to make

sounds, they must impart on them some sort of back-and-forth motion, perhaps by plucking the rubber band or balloon membrane and letting it reverberate, or by shaking the maraca back and forth. After these experiences, I notice that when the concept of *vibration* is mentioned again, the children are able to use it productively as a tool for predicting what other objects will be good noisemakers.

*Participation in cognitive apprenticeship and communities of practice.* According to Brown, Collins, and Duguid, as well as their counterparts Rogoff (1991) and Lave and Wenger (1991), the effectiveness of a situated learning environment is largely determined by the roles played by other learners and by teachers. Two notions that describe the ideal roles for teachers and learners are *cognitive apprenticeship* and *communities of practice*.

For Brown, Collins, and Duguid (1989), the idea of situated learning is not directive enough to inspire specific instructional strategies, so they propose the strategy of cognitive apprenticeship. In this model of learning, students learn specific practices and knowledge systems as do apprentices, through enculturation in authentic activity and social interaction with other apprentices and (more importantly) masters of the craft. If cognitive apprenticeship were to take place in schools, teachers would play the role of the masters of the academic domains, demonstrating how to use each discipline's conceptual tools to solve the problems of the world (Brown et al., 1989). Students, in turn, would pattern their behavior after the practices being conducted authentically by the teachers. If cognitive apprenticeship were to take place specifically in a design-based science classroom, teachers would act as expert practitioners of both design and inquiry. The apprenticeship model of learning suggests that if design is to be used to help students learn science, teachers must not only participate actively in the design task,

but they must also strive to be *masters* of the processes of designing and of investigating related science phenomena.

Similar to Brown and colleagues, theorists Lave and Wenger (1991) also find themselves unsatisfied with the explanatory power of situated learning. Consequently, they use the idea of *legitimate peripheral participation in communities of practice* to describe more accurately how learning takes place in social practice. They claim that one of the key problems of schooling is that nowhere within schools can students find the communities that actually *practice* the knowledge they are supposedly learning. Students have no access to adults from the communities of practice that truly utilize school knowledge: “Schoolchildren are legitimately peripheral, but kept from participation in the social world more generally” (Lave & Wenger, 1991, p. 104).

Communities of practice are important for children because they provide access to adults who are masters of using the conceptual tools. They are also important because they provide a network of peer learners, among which knowledge is circulated (Lave & Wenger, 1991). This phenomenon has been observed among children designing engineering artifacts (Roth, 1996). When one child makes a discovery related to solving the design problem, it spreads quickly through the classroom. This peer-to-peer instruction can be crucial when teachers find that their own demonstrations of a technique are not being assimilated by their students. Although masters of the trade are important members of any community of practice, sometimes their explanations are incommensurable with novice’s conceptual frameworks. In such instances, peer learning networks often fill in the information gaps.

The idea that legitimate peripheral participation is necessary for enculturation in a community of practice may be predictive of engineering's usefulness in science learning. This idea identifies shortcomings of current school learning communities and advocates for students

to be given access to real communities of practice, of which engineers may be one. Engaging in a practice that uses science knowledge is not the object of learning science, but a necessary condition for it. Participation in engineering design might be one way to satisfy that condition.

### *Distributed Cognition Theory*

Situated cognition theory provides a partial basis for design-based science instruction. This theoretical basis is strengthened by the theory of distributed cognition (Pea, 1993; Salomon, 1993). During an engineering design activity, an individual's knowledge about related science concepts can be unloaded to the tangible design products as well as to the other people participating in the design process. This sharing of knowledge may be one example of distributed cognition, which Bell and Winn (2000) define as *a person's individual cognitive acts plus the augmentation of other people, external devices, and cultural tools*. In other words, the notion of distributed cognition implies that cognition includes both the social and physical environments. This understanding is different from the situated view of cognition because it focuses on the amplification of individual cognition for a given task, rather than on the contextualizing of cognition for future use. From the distributed cognition perspective, social and physical factors *multiply* an individual's thinking, while in the situated cognition perspective, they *ground* thinking. Distributed cognition theorists look for ways that an individual's cognitive load is lightened during a certain activity. Situated cognition theorists look for ways that the situation surrounding an individual's cognition has lasting impact on future tasks (i.e., on learning). The two views are not contradictory, but they do come from different perspectives.

*Three characteristics of distributed cognition environments.* Hutchins (1995) proposes three characteristics of any distributed cognition environment. First, in such an environment,

*knowledge is shared* or communicated among multiple people or by an external device that makes knowledge visible on some sort of display. Second, in a distributed cognition environment, all shared *knowledge is pooled* together, so that any member of the environment can use any of the knowledge for the benefit of all. Third, the members of a distributed system are *reliant on each other* for the completion of the task. If this distributed cognition theory is relevant to design-based science instruction, then I should be able to locate these three characteristics within a hypothetical engineering design activity in a science class (for another example within a chemistry class, see Bell & Winn, 2000). In a classroom engineering design activity, the cognitive system includes students and artifacts, at the very least. When students engage in engineering design, they certainly communicate their knowledge, both through the plans they share with each other, and through the functionality of their design artifacts. They also pool their knowledge, since the combination of multiple students' ideas is necessary if a small group is to succeed in creating one single solution to the design problem. Finally, because the success of the design artifact is dependent on students' science knowledge, the students and the artifacts do indeed rely on each other to complete the cognitive task.

*Fostering cognitive residue within learning environments.* In addition to Hutchins' three characteristics, distributed cognition theory also offers the helpful construct of *cognitive residue* (Bell & Winn, 2000; Salomon, Perkins, & Globerson, 1991). Humans generally assume that when they appropriately use technological tools as part of a cognitive system, they are more productive and their intellectual capabilities are enhanced. However, what is not quite as obvious is that those technological tools can leave a sort of residue that supports intellectual activity later, even when the tools are no longer present:

Exposure to artifacts, whether they have been designed to help us internalize and develop cognitive skills, like the Writing Partner, or not, like television, leaves a residue that can serve individuals well when they must perform tasks in the absence of the tool. (Bell & Winn, 2000, p.

131)

Theorists often focus on computers as technological tools, but many other human-created artifacts could play this role. For example, imagine a geometry student who frequently uses a protractor to draw precise polygons as she completes a homework assignment on external and internal angles. When she takes an examination on the same topic, she does not have a protractor with her. However, her extensive experience with the protractor has left a cognitive residue that enables her to work quickly through the problems that require visualization of angles.

This idea of cognitive residue is implicit within the popular instructional technique of *scaffolding* students' learning by providing a support for a complex task and then gradually removing that support until the student can complete the task independently (Puntambekar & Hubscher, 2005; Puntambekar & Kolodner, 2005). Scaffolding methods include verbal reminders, written prompts, scripts for collaborative tasks, and models of effective practices. When they are first provided, these types of assistance serve the purpose of reducing the students' cognitive load so that the main instructional task can be completed. The assisting scaffolds are gradually omitted from instructional materials, but the students retain their *cognitive residue* – such that the now absent scaffolds provide internal cognitive cues rather than external cognitive aids.

In the school science setting, engineering design artifacts might also function as learning scaffolds and thus produce cognitive residue. Although design products are artifacts with an end in themselves rather than artifacts intended to be cognitive tools, they might provide a lasting cognitive effect for students who learn new science knowledge to solve a design problem. A design artifact might embody a students' newly formed science concept, and recalling the artifact might trigger recall of the science concept.



Additionally, one's human partners in a cognitive task can leave cognitive residue. Just as distributed cognition in general has both social and physical aspects, cognitive residue also has both social and physical connotations. Recalling the words and actions of classmates and teachers might help students to recall the related science concepts. However, for cognitive residue from artifacts and people to assist with conceptual recall, students will likely need explicit instruction in how to recognize that their cognition is distributed and in how to use artifacts and people as cognitive tools.

My explorations of situated cognition theory and distributed cognition theory have shown how both frameworks can inform efforts to use engineering design to foster science learning. However, it remains to be seen whether these theoretical predictions bear fruit in the empirical setting of the classroom. I now turn to a survey of what design-based science learning looks like in real elementary and middle schools.

#### *Section 4. Review of Empirical Studies of Design-Based Science Instruction for Children*

In the following paragraphs, I review how the educational research literature describes five recently studied approaches to design-based science instruction at the elementary to middle school level: design-based modeling (Penner, Giles, Lehrer, & Schauble, 1998), engineering for children (Roth, 1996), engineering competitions (Sadler, Coyle, & Schwartz, 2000), project-based science (Krajcik & Blumenfeld, 2006), and Learning by Design™ (Kolodner, 2006). These approaches were chosen for review because they are most often cited in the research literature, and because information is available about their theoretical background, principles of curriculum design, and findings on learning. Table 3 lists the criteria on which this review focuses. These criteria are consistent with the main issues raised by situated and distributed cognition theory: what tasks are considered to be cognitive activity, how learning is related to cognitive activity, what practices are used to promote learning, and what counts as evidence of learning.

*Table 3. Criteria for Reviewing Approaches to Design-Based Science Instruction*

<b>Criterion</b>	<b>Description</b>
<i>Understanding of Design</i>	What constitutes <i>design</i> in the approach? What kind of activity is it?
<i>Sample Design Task and Science Concepts</i>	What do students design, and what science are they supposed to learn? How does design as a cognitive activity connect to learning about science?
<i>Instructional Practice</i>	What, if any, pattern of instructional activities does the approach prescribe? In what practice does the classroom community engage? What is the teacher's role?
<i>Findings on Learning</i>	What kinds of student learning have been found by the proponents of the approach? How do they demonstrate enhanced cognition?
<i>Contributions and Challenges</i>	What characteristics would persuade an educator to adopt this approach, and what characteristics would lead an educator to decline to use it?

Both of the theoretical frameworks discussed in the previous section inform how I conceive of these review criteria, since both frameworks imply unique ways to understand design, to relate design tasks to science concepts, to plan instructional practice, and to specify evidence of learning. From the situated cognition perspective, design would be understood as an

authentic cultural situation in which certain cultural tools are exercised and certain communities of practitioners are involved. The relationship between design tasks and science concepts would be described as the deepening of science understanding through its continued and situated use to accomplish a design task. Instruction would follow the form of an apprenticeship, where the students learn through enculturation in the physical and social activities associated with design. The teacher would play the role of the master of the design craft. Learning would be defined by the ability to use science ideas in real life situations.

From the distributed cognition perspective, design would be understood as an activity that augments an individual's cognitive landscape with physical tools as well as with other people. The relationship between design tasks and science concepts would be described as the unloading of science knowledge onto the design artifacts under construction. Instructional practice would teach students how to use design artifacts and teammates to aid in their science learning. The teacher would play the role of an additional resource for analysis and conversation. Finally, evidence of learning would consist of a properly functioning artifact, which signifies the successful unloading of a science concept into the physical world.

On two criteria – instructional practice and evidence of learning – the implications of the two cognitive theories contradict each other. Concerning instructional practice, situated cognition theory suggests that the teacher should play the role of the master designer, whereas distributed cognition theory would position the teacher as merely one resource among the many available to the student. Because the demonstration of learning strategies is so essential to elementary school pedagogy, for this particular issue of the teacher's role, the situated cognition view should prevail over the distributed cognition view. For elementary school students, it is more important that the teacher models effective design behavior than it is that the teacher stands by as an

optional resource. Concerning evidence of learning, the conflict lies between the situated view that learning is defined by the application of science concepts to real life and the distributed view that learning is defined by the successful functioning of the current design artifact. Again, in this conflict, the situated view takes precedence. Although a working device typically implies science knowledge, such knowledge is not ultimately useful to the student unless he or she can apply it to other situations. Ideally, of course, learning displayed by a working artifact would promote deeper learning that could be applied to later life situations.

Table 4 summarizes the main characteristics of the five design-based science approaches surveyed in the subsequent paragraphs, and Table 5 situates all five approaches along the design/inquiry continuum.

*Table 4. Characteristics of Five Representative Approaches to Design-Based Science in Elementary or Middle School*

<b>Approach and Authors</b>	<b>Age Level</b>	<b>Sample Design Task and Associated Science Concepts</b>	<b>Findings on Learning</b>	<b>Main Contribution</b>	<b>Challenges of Implementation</b>
Design-Based Modeling  (Penner, Giles, Lehrer, & Schauble, 1997; Penner et al., 1998)	6-8 years	Task: Design a model of the human elbow. Learn: Importance of constraints on motion, arm as 3rd-class lever, math relationships within levers, modeling in general.	Mainly science process-oriented learning. Improved recognition of the importance of a model's functional qualities. Minimal gains in understanding the arm as lever.	Design skills can be improved simultaneously with science process skills and understanding.	Difficult to move children from summarizing patterns of artifact performance to explicit understanding of the underlying science principles.
Engineering for Children  (Roth, 1996, 1997, 2001)	9-12 years	Task: Design a strong tower from common materials. Learn: Stability, shapes, forces. Task: Build a machine that uses simple machines. Learn: Physics of simple machines.	Six kinds of learning, almost all process-oriented: (1) dealing with complex, open-ended tasks, (2) new meanings for materials and artifacts, (3) being conscious of participation in design, (4) negotiating with classmates, (5) using a variety of tools in interesting ways, (6) communicating about design.	Main emphasis is on classroom discourse (talking and writing). In order for science learning to occur, discourse must hold as much weight as designing.	Open-ended, no clear instructional sequence or definition of what constitutes a good design task; the effectiveness of the design context depends on the individual teacher.
Engineering Competitions  (Sadler, Coyle, & Schwartz, 200)	10-15 years	Task: Build a cardboard house that stays coolest under a heat lamp; Learn: Thermal conductivity.	Only process-oriented learning comprehensively measured. Significant gains on 8 of 11 items that tested science process skills (variables and hypotheses, experimental design, graph interpretation), with 457 students tested.	Stress importance of tests against nature and of carefully designed challenges with "large dynamic ranges" of performance.	Little rationale for how specific design challenges connect to specific science concepts. Quite difficult to find devices with as large a dynamic range as they suggest.

Project-Based Science  (Krajcik & Blumenfeld, 2006; Tal, Krajcik, & Blumenfeld, 2006)	11-14 years	Task: Construct a mini “helmet” that will protect an egg in a small rolling cart. Learn: Force, mass, velocity, acceleration, Newton’s laws.	Quantitatively measured conceptual learning. Students (of 63 teachers) who participated in at least one PBS unit performed significantly better on state standardized science tests than matched students who did not participate in any unit.	Place high value on authentic, real-world goals for learning, and strive to find goals and questions that are relevant to students.	Conceptual learning very dependent on teacher. In one study, one classroom had pre-post gains three times higher than other classrooms.
Learning by Design™  (Kolodner et al., 2003; Kolodner, 2006)	11-14 years	Task: Design an optimal balloon-powered coaster car Learn: Basic mechanics, Newton’s laws of motion	Both process-oriented and conceptual learning were measured. LBD students showed higher gains than matched peers on multiple choice pre-post tests, and better performance in designing experiments, planning data collection, and collaborating.	Recognize that classroom culture conducive to design is not created automatically, and specify “ritualizing practices” to help construct culture.	Conceptual learning is highly dependent on teacher competency and attitudes. Some teachers leave program because they are not able to adjust to a new kind of classroom control.

*Table 5. Situating the Five Representative Approaches on the Design/Inquiry Continuum*

The Continuum Between Design and Inquiry in Science Instruction	Locations of the Five Approaches to Design-Based Science
Inquiry only	Project-Based Science  Design-Based Modeling  Learning By Design™  Engineering for Children Engineering Competitions
Inquiry supported minimally by design endeavors	
Inquiry supported substantially by design endeavors	
Inquiry and design equally supporting each other	
Design supported substantially by inquiry explorations	
Design supported minimally by inquiry explorations	
Design only	

*Approach 1: Design-Based Science Modeling*

Penner and colleagues’ approach, design-based modeling, engages children in the design of three-dimensional artifacts as a context for learning about scientific modeling (Penner, Giles, Lehrer, & Schauble, 1997; Penner, Lehrer, & Schauble, 1998).

*Understanding of design.* Penner et al. conceive of design tasks as problem-solving activities in which thinking and manipulation of tools and materials result in the construction of

an artifact. They assert that one major category of designing in which scientists very often engage is the design of *models* of phenomena under study. Designed models can enable deeper investigation of science concepts as well as exploration of mathematical relationships. The cyclical nature of design allows students to enact cycles of “model building, evaluation, and revision” (Penner et al., 1998, p. 431). For Penner et al., the real goal is model-based reasoning, and artifact design is the means to this end.

*Sample design task and science concepts.* Penner et al. (1997, 1998) give first, second, and third graders the task of designing a functional model of the human elbow with the materials provided by the teacher. They hope that through this design work, students develop beliefs about modeling in general, learn how the arm functions like a third-class lever, and explore the mathematical relationship between force, muscle attachment point, and load position.

*Instructional practice.* The design-based modeling approach of Penner et al. is not dependent on a specific prescribed sequence to be followed in the classroom; however, from their reports, one can infer a general timeline of classroom events, which take place over nine 45- to-60-minute class sessions (Penner et al., 1997; Penner, Lehrer, & Schauble, 1998):

1. Teacher describes design task and allowed materials.
2. Students plan and build designs in small groups.
3. Students share updates and reflect through teacher-facilitated class discussion.
4. Students conduct model testing and evaluation.
5. Students revise models.
6. Students present and discuss revised models
7. Teacher leads science investigation with built models (1998 study only).

As these classroom events unfold, the teacher uses class discussions to emphasize concepts of structure and function and to highlight the importance of functional rather than perceptual qualities of models. Prompting students to struggle with these ideas is the ultimate goal of the instructional activities. From the perspective of situated cognition theory, the task of coming to

consensus on what constitutes a high-quality model is an authentic dilemma, and it provides opportunities for extended discussion and reasoning.

On the continuum between design and inquiry in the science classroom, design-based science modeling is located near the center, where scientific inquiry is supported substantially by design endeavors. In a design-based modeling activity, the primary goal is to engage students in an investigation of science concepts or phenomena. Enriched inquiry is the main objective, and design endeavors play a substantial, enabling role in achieving this objective.

*Findings on learning.* Looking for evidence of ideas about models, Penner and colleagues analyzed the constructions and conversations of the first, second, and third graders who participated in the design-based elbow modeling activity. In the third grade class, they found that by the end of the design-based activity, students could fluently discuss structure and function, modeling as a way to represent function, general classes of human joint motion, and math as a means to represent natural phenomena. However, the third graders did not explicitly discuss new knowledge about the principles of leverage, which had been one of the curriculum's main science learning goals. In the first and second grade class, Penner et al. (1997) found that the first graders recognized the importance of functional qualities of models much more frequently than did older students who had not participated in designing models. In both studies, Penner et al. found mainly evidence of process-oriented learning; students learned about models, but they were not found to make much progress in their conceptual understanding of levers.

*Contributions and challenges.* Penner et al. experimentally explored the use of design activity to help children build understandings about scientific models. Their trials exhibit several successes that might inspire newly created curriculum. By participating in Penner et al.'s instructional activities, children were able to combine work on design skills with work on the

understanding of science practices, namely, modeling. This simultaneous skill-building is an achievement. This success was partly enabled by Penner et al.'s generous view of children's designing: they allow children's design solutions, or artifacts, to *evolve* continuously with successive class discussions about the science concepts embedded in the design task.

We can also find several instructional challenges within Penner et al.'s studies. When student-built models were used as a context for scientific investigation, significant teacher scaffolding was needed for any data recording steps, including the creation of graphs and tables. Further, once data records were made, it was difficult to move children from summarizing artifact performance data patterns to building explicit understandings of the underlying science principles (1998). This finding leads Penner et al. to conclude that even when using design activities as a context for science investigations, "considerable effort and ingenuity are necessary to develop children's understanding of scientific inquiry as an orientation toward understanding the causal mechanisms behind effects" (1998, p. 448).

### *Approach 2: Project-Based Science*

Penner et al. use design projects specifically to focus children's thinking on modeling in science. Proponents of other approaches to design-based science instruction envision a broader range of science concepts that can be investigated through projects that involve design. Krajcik and colleagues have incorporated design-like activities into middle-school science units on water quality, air pollution, waste management, force and motion, and simple machines (Krajcik, Blumenfeld, Marx, Bass, Fredricks, & Soloway, 1998; Krajcik & Blumenfeld, 2006; Rivet & Krajcik, 2004; Schneider, Krajcik, & Soloway, 2002; Tal, Krajcik, & Blumenfeld, 2006). Their approach, *project-based science*, is located closer to the *inquiry* end of the design/inquiry



continuum than to the *design* end. In Krajcik et al.'s project-based science units, design plays only a supporting role within inquiry investigations.

*Understanding of design.* In describing their project-based science approach, Krajcik et al. do not frequently use the vocabulary of designing and engineering. However, were a professional engineer or architect to examine their curricular activities, he or she would see in them many design-like tasks. Just as designers produce tangible, shared design products, the construction of physical, public artifacts is an essential part of the project-based science curricular approach. Krajcik et al. intend for their project-based instructional interventions to foster deep science understanding through student engagement in real-world problems modeled after adults' professional activities (Krajcik & Blumenfeld, 2006). Each project-based science curriculum must include five key features: (1) an initial driving question or problem; (2) exploration of the driving question through "authentic, situated inquiry;" (3) collaboration between teachers, students, and community members; (4) scaffolding with learning technologies so that students can accomplish activities beyond their unassisted capability; and (5) creation of tangible and shared artifacts (Krajcik & Blumenfeld, 2006, p. 318).

Krajcik et al. position the driving question, which is based on a real-world problem, as the instructional feature that situates students' cognition within a meaningful task. Because the driving question plays a central, situating role, while the constructed artifact plays a more secondary, motivating role, the project-based science approach is located toward the inquiry-only end of the design/inquiry continuum. In each project-based science unit, the main teaching goal is to lead students toward evidence and reasoning that answer the unit's driving science question. Artifact design activities serve to engage students in the unit and motivate their exploration of the driving question, but they are not the unit's focal point. Project-based science is an inquiry-

based approach to science instruction in which design endeavors play a minor, though important, supporting role.

*Sample design task and science concepts.* In one project-based science unit (Tal, Krajcik, & Blumenfeld, 2006), the driving question is: Why do bicycle riders need to wear helmets? During the artifact construction portion of the unit, this question is reconceived as a design problem: How can I construct a miniature helmet that will protect an egg in a small rolling cart? The egg represents a person, and the cart represents a bicycle. The instructional activities that lead to problem solution are intended to help students learn the concepts of basic mechanics, including ideas of force, mass, velocity, and acceleration, and their relationships described by Newton's laws.

*Instructional practice.* Descriptions by Krajcik et al. indicate that project-based science units do not all adhere to exactly the same order of events. However, all units, which last from eight to 15 weeks, do include some form of the following activities (Krajcik et al., 1998; Krajcik & Blumenfeld, 2006):

- Teacher introduces real-world “driving question,” usually through an “anchoring experience” (Krajcik & Blumenfeld, 2006, p. 321-322).
- Students work in groups to plan experiments and create designs to answer questions.
- Students construct apparatus (artifacts) and collect data.
- Students and teachers interpret data and write science conclusions.
- Students present their apparatus and conclusions and receive feedback.
- Students rewrite, replan, and rebuild.
- Students present again; teacher facilitates discussion.

Because these steps do not follow each other in a linear fashion, Krajcik et al. (1998) refer to them as the “Investigation Web” of project-based learning activities (p. 316). While students move from node to node on the web, the teacher is constantly focusing students' attention on the driving question and assisting with interpretation of data that may address the question.

*Findings on learning.* By 2004, five middle-school project-based science units had been used by at least 63 teachers in 26 schools (Krajcik & Blumenfeld, 2006). Students who participated in at least one of the units were found to have increased science conceptual knowledge. They performed significantly better on state standardized science tests than a matched group of students who did not participate in any unit. Students who were exposed to more than one unit performed significantly better than students who participated in only one unit.

*Contributions and challenges.* The strength of the project-based learning approach to science instruction lies in its recognition that students benefit from having authentic, real-world goals for their learning. Project-based science units all begin with anchoring experiences and driving questions, and these motivators help students see scientific inquiry as both valuable and contextualized.

Despite this strength, Krajcik et al. do acknowledge several challenges of implementing their approach. First, there is danger in placing too much confidence in the motivational power of driving questions. According to Krajcik and Blumenfeld (2006), their questions do not always evoke in students a desire to learn, nor do they always help students produce knowledge with clear connections to science concepts. Second, successful learning through project-based science units requires students to collaborate well with each other, and this does not naturally happen in middle school. Third, students need prompts that ask them to reflect on similarities and differences between ideas, but project-based units do not necessarily provide those prompts, so the responsibility falls to the teacher. In fact, student learning seems highly dependent on teacher characteristics. For example, Tal, Krajcik, and Blumenfeld (2006) found in one study that students with one teacher improved three times more between pre-test and post-test than did students with other teachers. Tal et al. (2006) explained that this discrepancy was a result of

differences in teachers' abilities in classroom management, content knowledge, attitudes and expectations for students, facilitation of reasoning, and facilitation of collaboration. The possibility that learning gains are dependent on such fundamental teacher characteristics represents a drawback not only of Krajcik et al.'s approach, but of all approaches to using design-like activities for science learning.

### *Approach 3: Engineering Competitions for Middle School Science*

Sadler, Coyle, and Schwartz (2000) have studied another strategy for using design projects to help middle school students learn science. They confront students with very carefully specified engineering challenges and expect that students will develop understandings of science principles as they iteratively struggle to create the optimal engineering design.

*Understanding of design.* Sadler, Coyle, and Schwartz (2000) refer to the projects they assign to students alternately as "engineering challenges" or "design challenges." These challenges task students with designing and building working devices that satisfy constraints. Sadler et al. explicitly describe design as the real-world application of science, and they assert that in their curricular materials, design is the primary activity undertaken by students. It is not merely a backdrop or context.

For each of Sadler et al.'s design challenges, students are given initial prototype instructions, and their goal is to iterate and improve that prototype. Students' cognitive efforts are located within the prototype iteration cycles, and Sadler et al. hope that students discover critical science principles through their experiences of success and failure. For this discovery learning to occur, the design challenges need six essential elements: (1) clear goals that prompt action and self-evaluation of performance, (2) tests against nature rather than other students, (3)

large dynamic ranges in device performance, (4) initial prototype instructions, (5) opportunity for multiple iterations, and (6) purposeful record-keeping and presenting of results.

*Sample design task and science concepts.* Sadler, Coyle, and Schwartz (2000) have created six design challenge modules: bridges, electromagnets, wind turbines, solar house, electric battery, and gravity car. In the solar house module, the students' design challenge is to build the cardboard house that stays the coolest under a heat lamp. Sadler et al. do not specify the science content learning objectives for this design task, but one might assume they all relate to topics of thermal conductivity and heat transfer.

*Instructional practice.* Sadler et al. (2000) mention roughly six types of activity that occur in each of the middle-school engineering modules, which last for five to ten class periods.

1. Students listen to an audio taped scenario that specifies the design challenge.
2. Students copy the supplied initial design to construct their first prototypes.
3. Students and teacher brainstorm variables that affect the prototype's performance.
4. Students and teacher decide which variables to investigate.
5. Students conduct several rounds of construction and testing, competing against nature.
6. Facilitated by the teacher, students engage in record keeping and reflection, which includes storyboarding.

Engineering competitions for middle school science is essentially a design-based approach in which design is supported minimally by inquiry explorations. This means that on the continuum between design and inquiry in classroom science, Sadler et al.'s engineering competitions are located opposite Krajcik et al.'s project-based science. Of the five approaches reviewed in this paper, Sadler et al.'s approach is situated nearest to the design-only end of the continuum. However, it does not consist exclusively of design activities, since questions about scientific phenomena underpin each of the engineering design challenges. The main objective is always to design a successful artifact, but each design experience is followed by reflection focused on the related science concept.

*Findings on learning.* Sadler et al. (2000) administered a pre-post assessment of process-oriented science knowledge (variables and hypotheses, experimental design, graph interpretation) to 457 students of 12 teachers spread across the U.S. They found significant gains on eight of the eleven items, and the mean assessment score increased significantly from 0.437 to 0.553 (out of 1.0 maximum). They report on only one conceptual knowledge test, for the five-day electromagnets module. Seventeen sixth graders took the test, and the mean score rose from 0.556 out of 1.0 on the pre-test to 0.689 out of 1.0 on the post-test. There was no control or comparison group.

*Contributions and challenges.* Sadler et al.'s approach to using design challenges in science instruction makes several positive contributions to the field. First, the approach in general recognizes the critical role of design tests, and specifically points out the importance of requiring students to test their designs against nature rather than against other students' designs. Second, Sadler et al. (2000) introduce the notion of the "large dynamic range" (p. 17), which refers to creating design challenges so carefully that diligent students can produce very noticeable improvements in artifact performance. It is not easy to conceive of design tasks that have large dynamic ranges, but Sadler et al. stress their importance for students who are not yet developmentally ready to react to small, subtle improvements. Finally, Sadler et al. are insightful in providing for each curriculum module an initial prototype design – a "simple working model, albeit a poorly working one" (2000, p. 319) – because these prototypes serve as models that help students understand the goals of each design challenge.

Despite these important contributions, Sadler et al.'s approach also has its limitations. In their report of their research, Sadler et al. mention no specific science learning objectives, nor a clear rationale for how their design challenges lead to conceptual change in science. They cite

multiple iterations, purposeful record keeping, and storyboarding as the means for bringing about conceptual change in science, but they do not explain how those means function. Their approach also lacks specificity about the role of whole-class science discussions and the role of the teacher in design challenge learning environments.

#### *Approach 4: Engineering/Technological Design for Children*

Roth is another scholar who regularly uses the term *engineering* to describe the activities of children in design-based science instruction. He uses multiple perspectives to analyze attempts to teach science to children through design activities (Roth, 1996, 1997, 2001).

*Understanding of design.* Roth equates design with the process followed by engineers, and he asserts that it consists of creating initial sketches and building plans, translating these plans into other representations, constructing three-dimensional prototypes, performing, recording, and analyzing tests, and finally putting the product into production (2001). This entire set of activities is “the design phase of an artifact” (Roth, 2001, p. 771). Roth proposes that this kind of design can be used as a context for learning science, but three criteria must be met: (1) students’ ideas must be made inspectable and arguable in the form of diagrams and three-dimensional artifacts; (2) students must engage in prototyping, which allows for their thinking to be made concrete in the world; and (3) the class must become a community of learners where whole-class conversations can happen (Roth, 2001). As his emphasis on argumentation and community practices suggests, Roth’s work is explicitly aligned with the situated cognition view of learning.

*Sample design task and science concepts.* Roth’s approach has been enacted in two different design-based science units. In the first, implemented with fourth and fifth graders, the

design task was to construct strong structures out of common craft materials, and the science learning objective was to improve understandings of stability, shapes, and forces (Roth, 1996). In the unit enacted with sixth and seventh graders, the design task was to construct simple machines, and the learning objective was to become fluent with the physics of simple machines (Roth, 2001).

*Instructional practice.* Roth's approach to design-based science instruction is loosely structured, partly because units last for many instructional periods. The fourth/fifth-grade unit lasts for 13 weeks, with two 90-minute sessions per week, and the sixth/seventh-grade unit lasts for 16 weeks. In general, four activities occur throughout both units:

1. Students brainstorm construction techniques for their designs.
2. Students conduct teacher-prompted background research.
3. Students work with partners to construct artifacts and keep notes in engineering logbooks.
4. Teacher facilitates periodic whole-class discussions.

The sixth/seventh-grade unit includes two additional activities: an initial (fictional) call for proposals and periodic small-group investigations stipulated by the curriculum.

While Roth's instructional interventions are explicitly centered on extended design tasks, he also places emphasis on scientific argumentation and discourse. Thus, on the design/inquiry continuum, Roth's engineering for children approach is located in the region where design-based instruction is supported substantially by inquiry explorations.

*Findings on learning.* Roth provides mainly narrative reports of learning. In the 1996 fourth/fifth grade study, he observed six "dimensions" of learning (p. 157): (1) dealing with complex, open-ended tasks; (2) generating new meanings and uses for materials, tools, and artifacts; (3) being conscious of participating in the design process while constructing artifacts, (4) negotiating one's own plans and understandings with those of classmates, (5) competently using a variety of tools and materials in interesting ways, and (6) communicating in oral and



written form about engineering design. During the sixth/seventh grade unit, Roth observed that students learned how to design tests for physical artifacts, how to provide justification for design decisions, and how to reason scientifically about mechanical advantage, using both diagrams and language. All of these kinds of learning, except for the second dimension of the fourth and fifth graders' learning, would be classified as process-oriented learning. The exception, generating new meanings for materials and tools, could be considered creative learning.

*Contributions and challenges.* The unique strength of Roth's approach lies in the emphasis he places on students' discourse, enacted in both talking and writing. He asserts that in successful design-based science activities, students' designing must be constantly accompanied by students' discourse. Roth's mantra is that the process is more important than the product. He acknowledges that student learning does not happen when design consists only of tinkering until a device works: "If students are just operating on materials and not forced by the situation to also represent them, scientific discourse ...is not likely to occur" (2001, p. 785). Instead, design-based science must require students to analyze and explain their designs' failures (Roth, 2001).

The main challenge that would face an educator implementing Roth's approach is its open-endedness. It does not explicate an instructional sequence or define what constitutes a good design task. The effectiveness of any particular design context is determined by the teacher, since Roth insists that the teacher must make salient the aspects of designs and artifacts that are relevant to science (2001). Therefore, for Roth's approach to foster science learning, the teacher must possess considerable knowledge of the way in which science principles are embodied in tangible technologies. The curricular materials themselves do not spell this out.

*Approach 5: Learning by Design™*

In contrast to Roth's somewhat elusive descriptions of his instructional approach, the Learning by Design™ approach to science learning has been spelled out in extensive detail (Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998; Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, et al., 2003; Kolodner, 2006). I conclude my review with this approach because it provides the most complete set of ideas for the reader to consider. Learning by Design™ curricular materials, for middle-school science classrooms, have been developed and studied by Kolodner and her research group at Georgia Tech since the mid-1990s.

*Understanding of design.* Kolodner et al. have trademarked the name for their pedagogy and materials; it is called "Learning by Design," or "LBD." Kolodner (2006) defines LBD as a "project-based inquiry approach" in which "students learn by attempting to achieve design challenges" (p. 228). The design challenges problematize students' application of their science knowledge by creating real dilemmas whose solutions require operational science concepts. Within the LBD approach, the action of "designing" includes the "full range of activities that a professional designer (e.g., engineer, architect, industrial designer) engages in to fully achieve a design challenge" (Kolodner et al., 2003, p. 504). For these activities to enable learning in a middle-school science classroom, certain pedagogical considerations must be made. Kolodner (2006) lists four key elements of the LBD pedagogy: (1) explicit classroom scripts; (2) specific roles for teachers and students in both active and conversational activities; (3) clear sequencing of individual, small-group, and whole-class activities; and (4) specifically-chosen physical materials and text resources (2006).

*Sample design task and science concepts.* Numerous LBD units have been developed and studied. Each unit centers on an overarching design challenge that requires a series of scientific

investigations to be conducted before it can be successfully completed. In one unit, *Vehicles in Motion*, the grand challenge is to design a mechanically powered miniature vehicle that can climb a 10-cm hill (Kolodner et al., 2003). Three mini-challenges lead up to this grand challenge: students construct optimal low-friction ramp carts, balloon-powered coaster cars, and rubber-band powered vehicles. The specific components of these challenges are intended to help students learn the science of basic mechanics, including Newton's laws of motion.

*Instructional practice.* Kolodner et al. describe a consistent pattern of classroom activities that is used by each of the LBD units, which typically last for about eight weeks. As students enact the following steps, they move back and forth from an "investigate & explore" cycle to a "design/redesign" cycle (Kolodner et al., 2003, p. 511):

1. Teacher leads students through a "launcher unit" that reviews general processes and attitudes necessary for design and scientific inquiry (Kolodner et al., 2003, p. 512). This is the first of several LBD classroom rituals.
2. Teacher introduces challenge, and students use instructions to construct initial device.
3. Students investigate to find important performance-affecting variables.
4. Students work in groups to design and conduct experiments on one chosen variable.
5. Students draft scientific principles called "design rules of thumb" and share them with each other in a "pin-up session" (Kolodner et al., 2003, p. 511, 515).
6. Students incorporate rules of thumb in more investigations of device performance.
7. Students design and construct revised devices.
8. Students consider all final designs in a "gallery walk," where they focus on why designs worked as they did (Kolodner et al., 2003, p. 516).
9. Teacher facilitates whole-class reflection and individual project reports.

The purpose of the repeated design and investigative cycles is "to scaffold the kinds of deliberation that result in students recognizing and revising their understanding, skills, and practices" (Kolodner, 2006, p. 230). Because the Learning by Design approach calls for continuous back-and-forth between the design cycle and the investigative cycle, it is located at the center of the continuum between design and inquiry in the science classroom. In Learning by Design units, design and inquiry equally support each other as processes that enable meaningful science learning.

*Findings on learning.* By 2003, Learning by Design units had been evaluated in over 24 classrooms with over 3500 students. In 2006, researchers quantitatively compared about a dozen LBD classrooms with peer-matched classrooms not using LBD units. They measured both conceptual knowledge and process-oriented knowledge. The LBD students achieved higher gains on conceptual multiple-choice pre-post science tests, and they exhibited better performance in the processes of designing experiments, planning data collection, and collaborating with others.

*Contributions and challenges.* Due to Kolodner et al.'s clear and thorough articulation of Learning by Design units and results, it is an approach that brings several important issues to the forefront of efforts to create design-based science curriculum. First, like Roth, Kolodner et al. recognize the great importance of talking and reporting to support students' learning through design. They say that classroom discourse is essential and that learning is not likely to occur if students are not asked to share their ideas and results repeatedly. Accordingly, the Learning by Design instructional materials include explicit directions for teacher-facilitated but student-led discourse. Besides highlighting the centrality of discourse to student learning, the LBD approach also points out the importance of classroom culture and reveals that classroom cultures conducive to design are not created automatically. Through their launcher units, which include analyzing videos of scientists and engineers at work, Kolodner et al. have attempted to provide the seeds for growing a design-conducive culture. Three cultures are actually essential to the LBD approach: a culture of collaboration and independence, a culture of iteration, and a culture of scientific reasoning. The third important contribution of Kolodner et al.'s approach is its recommendation to use "ritualizing practices," including whiteboarding, pin-up sessions, gallery walks, and messing about. These practices connect the *action* of a design challenge to the *discourse* of science reasoning.

Like the other four approaches, Learning by Design also presents some challenges. First, as in the units studied by Roth and Krajcik et al., student achievement in Learning by Design units is very dependent on teacher competencies and attitudes. Second, it is not clear if the launcher units and main units succeed at establishing the three essential cultures, or if teacher leadership and initiative beyond the provided materials are necessary for adequate culture creation. If this didactic intervention is necessary, then the units may not meet the situated cognition expectation for providing an authentic context for learning. Third, LBD researchers have found that it is hard for students and teachers to move on when not all devices are working efficiently. This might be an unavoidable problem for an instructional approach with so much back-and-forth movement among activities.

*Section 5. Discussion: Synthesizing Theoretical Perspectives and Empirical Studies*

The above review of design-based science instruction illustrates that while all current approaches lead to some set of positive student outcomes, they also all present substantial challenges. No single approach can be identified as the strongest. Thus, the next task is to identify the common strengths and common omissions of the five approaches, in order to inform future efforts to develop elementary science curriculum based on engineering design activities.

*Common Strengths of Current Approaches*

*Common understanding of design.* To begin this synthesis task, I will identify the common characteristics of all five approaches discussed above, according to the criteria used for their review. First, and most importantly, all five approaches understand design as an activity whose goal is the construction of a design artifact. In all of the approaches, students are initially tasked with creating a functioning device or system that serves a purpose established by the instructor. The resulting artifact is then an essential factor in students' learning.

*Common links between design artifacts and science learning.* All five approaches assign to the design artifact a key role in students' science learning. In Penner et al.'s design-based modeling (1998), the artifact takes the form of a model and serves as a medium for a later scientific investigation. According to Roth (1996), design artifacts become thinking tools, representations of process, and a backdrop for classroom discussion and sense-making. In the work of Sadler et al. on middle school engineering competitions (2000), the artifact is a functioning device that plays the part of a test-bed for students' science conceptions; if their science conceptions are non-normative, their devices may not work. For Krajcik et al.'s project-based science (2006), artifacts motivate students' engagement in science, and the manipulation

of artifacts leads to the manipulation of science ideas, which leads to deeper understanding.

Finally, in Kolodner et al.’s Learning by Design™ (2003), the challenge of creating a functioning artifact provides motivation and opportunities for scientific reasoning and learning.

Table 6 reiterates the roles that the authors have attributed to the design artifacts and predicts the roles that would be attributed to design artifacts by the situated and distributed cognition perspectives.

*Table 6. Proposed Roles of Student-Constructed Design Artifacts in Science Learning*

	<b>Approach</b>	<b>The Role of the Design Artifact</b>
Empirical Studies	Design-Based Modeling	<i>A medium for scientific investigation.</i> “By first engaging the children in the modeling activity, the teacher was able to use the children’s designs to bridge to a study of mechanism” (Penner, Lehrer, & Schauble, 1998, p. 439).
	Engineering for Children	<i>A tool to think with, a representation of cognitive processes, and a backdrop for class discussion and sense-making.</i> “Emerging artifacts constitute a focus and backdrop for students’ discursive activities of talking, pointing, and gesturing, that allow them to make sense of each other’s utterances and to negotiate shared meanings in the face of ambiguity” (Roth, 1996, p. 157).
	Engineering Competitions	<i>A test-bed for how normative students’ science conceptions are.</i> “Design is a form of cognitive modeling that crystallizes a conceptual model into a physical embodiment, either on paper or as a physical entity” (Sadler, Coyle, & Schwartz, 2000 p. 304).
	Project-Based Science	<i>A physical representation of the manipulation and building of ideas.</i> As students build and reflect on artifacts, they “construct and reconstruct understanding” and “actively manipulate science ideas” (Krajcik & Blumenfeld, 2006, p. 327).
	Learning by Design™	<i>A source of motivation and location of opportunity for scientific reasoning and learning.</i> “Constructing working physical objects gives students the motivation to learn, the opportunity to discover what they need to learn, the opportunity to use science and to reason scientifically, and the opportunity to engage in and learn complex cognitive, social, and communication skills” (Kolodner, 2006, p. 229).
Theoretical Support	Situated Cognition Theory	<i>An authentic cultural goal that requires the use of science concepts as “tools”</i> “People who use tools actively rather than just acquire them, by contrast, build an increasingly rich implicit understanding of the world in which they use the tools and of the tools themselves. The understanding, both of the world and of the tool, continually changes as a result of their interaction” (Brown, Collins, & Duguid, 1989, p. 33).
	Distributed Cognition Theory	<i>A source of cognitive residue that aids students’ recall of conceptual knowledge in science.</i> “Working with artifacts leaves a cognitive residue that can usefully support intellectual activity, in the absence of the artifacts themselves, at later times” (Bell & Winn, 2000, p. 130).

*Common instructional practices and teacher roles.* Across all five approaches, there are several commonalities in how classroom instructional practice is structured. All students work in

groups, and interaction among students and improvement of communication skills are key goals of the teacher. As they work on solving the design problem, students engage in some kind of written or drawn record-keeping. At some point, students revise their designs or at least are given the option to revise their designs. In addition to their individual record-keeping and reflection, students reflect on their designing through participation in whole-class discussions.

As students engage in the activities necessary to create a design product, teachers assume particular roles. In all five approaches, teachers participate in training activities and begin to develop confidence teaching with design *before* they begin design-based instruction in their classroom. Teacher training (or background) and confidence is considered necessary for effective design-based instruction. Once trained, teachers provide guidance through the design activity on how students should incorporate science ideas and careful reasoning into their design solutions. Teachers believe that this scaffolding is essential if they are to prevent students from merely tinkering.

*Common claims about learning.* Finally, almost all of the approaches similarly present findings about science learning. With the exception of Krajcik et al., the authors provide more evidence for process-oriented learning than they do for conceptual learning. With data from written assessments, interviews, and classroom observations, they report on improvements in science process skills, such as designing investigations, using scientific instruments to gather data, and communicating with peers about science. The authors' treatment of conceptual learning is quite different. Roth does not comment on it at all, and Sadler et al. and Penner et al. report that they find little evidence of its improvement. Although Krajcik et al. and Kolodner et al. do report increased conceptual knowledge based on multiple choice test results, they describe students' process-oriented learning in much more detail.



*Elements Commonly Missing from Current Approaches*

Simply identifying the commonalities of current approaches to design-based science instruction does not thoroughly inform the development of future instructional material. I also must identify the elements that are *missing* from current approaches. These omitted elements are revealed by theory on professional engineering design as well as by theory on situated and distributed cognition.

*Elements from professional engineering design.* I propose that inclusion of certain elements of engineering design, as described in the scholarly literature, would bolster the authenticity and effectiveness of efforts to include design in elementary classrooms (Leonards, 2004). Some of the researchers referenced in this paper refer to their students' activities only as "design," and not as "engineering design." Perhaps their choice of the more basic term is precisely because their approaches lack some of the central elements of professional engineering design. Their decisions to omit these aspects of design may be intentional. However, I argue that by including specific features of engineering design, they could increase the likelihood that design tasks support science learning. Of course, there are countless aspects of professional engineering design that will always be omitted from approaches to design in the K-8 classroom, so here I present only the missing elements that seem most pedagogically central.

First, in professional engineering practice there is a *differentiation among several phases of design*, including conceptual design, preliminary design, and detailed design, with problem definition preceding all the phases, and design communication following them (Dym, 1994). A single professional engineer might only work within one phase. Conceptual design engineers decide on a general problem solution, while detailed design engineers work on separate parts of a

complicated product that has been already specified by others on the design team during conceptual and preliminary design (Dym, 1994). This distinction among phases is important to recognize because in an elementary classroom, children's design activities might not be confined to one phase; an individual student might plan a concept, test detailed implementations of that concept, and communicate a final design, all during one design assignment.

Scholars of engineering design point out that within each phase of design, engineers follow *multiple design processes and pathways*, so many that there is an entire field of research dedicated to describing engineering design processes (Finger & Dixon, 1983). Attempts to specify a single design process that should be followed by children when they engineer not only contradicts professional practice, it may also be counterproductive to children's design success.

Although engineers as a group use numerous processes and produce an infinite variety of products, the *universal feature across all engineers' practice is the creation of representations of their work*, representations both of the artifact and of the process of designing the artifact, whatever that process may be (Dym, 1994). A portion of those representations is always devoted to a clear articulation of the *resources* designers have and the *obstacles* they have to overcome (Tang & Leifer, 1991). The final set of representations produced by a collaborative engineering design team is primarily a set of *directions* for other people to reproduce products or systems, rather than the products or systems themselves (Dym & Little, 2004). The creation of prototype products or systems is a necessary part of designing, but the prototypes do not constitute the end product of engineers' work; they are a means to the end of a final set of directive representations.

Finally, no matter what form engineers' representations take, what process they follow, or within which design phase they work, their *activities always include analysis and testing of the work they are producing* (Bucciarelli, 1994). They might merely check that their conceptual

design satisfies all the requirements of the problem statement, or they might go into great detail using mathematical models to analyze the energy consumption of their particular design component. When children engage in design, testing should always be a part of their efforts, although this testing may take on many forms (Benenson, 2001).

*Elements from situated and distributed cognition theory.* In addition to considering the key characteristics of professional engineering design, the current approaches to design-based science instruction might also be enhanced by consideration of the theoretical frameworks of situated and distributed cognition. None of the current approaches describes the teacher as designing along with the students, but situated cognition theory suggests that learning might be improved by positioning the teacher as a *master* designer and the students as *apprentices*. Also, none of the current approaches ensures that students realize that as they engage in design together, they become a community of authentic practice – and that engineering design is a practice in which many real-world professionals daily participate.

In terms of distributed cognition theory, descriptions of current approaches lack discussion of *cognitive residue*, even though this notion might be helpful in characterizing the role played by the products of students' design processes. It prompts educators to ask whether students reference their design artifacts later in the school year, or in their school career, when they are struggling with related science concepts. Finally, design-based science instruction could benefit from devoting more attention to the idea of distributing cognition among students working in groups. In all approaches, students design in teams, but no approach is entirely successful at scaffolding students' interactions so that they use each other as cognitive resources.

*Drawbacks of Design-Based Science as an Instructional Approach*

Even if instructional designers were able to address all of the missing elements described above, any educator implementing design-based science would still be forced to make several significant tradeoffs. These general drawbacks to design-based science instruction must be acknowledged.

*Applicability of science content.* Not all elementary level science content can be investigated through engineering design activities. The research literature on design-based science abounds with examples of design challenges that involve macroscopic physical science concepts, such as Newton's second law (Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, et al., 2003; Krajcik & Blumenfeld, 2006), structural stability (Roth, 1996; Sadler, Coyle, & Schwartz, 2000), thermal conductivity (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman 2004), electrical resistance (Sadler et al., 2000), and simple machines and mechanisms (Penner, Lehrer, & Schauble, 1998; Roth, 2001; Rivet & Krajcik, 2004). However, it is much harder to find examples of design challenges that allow children to explore objects or phenomena that exist at microscopic scales (less than 1 mm) or very large scales (more 1 km).

It is also difficult to find examples of design-based science curricula that deal with concepts from the life, earth, and chemical sciences. There are a few notable exceptions, including life science activities that challenge students to design and construct functional models of organisms' structures (Penner, Lehrer, & Schauble, 1998). And in the area of earth science, one Learning by Design™ unit addresses the topic of earth surface processes by asking students to design a system for managing erosion, and another unit poses the task of designing underground tunnels to teach concepts related to ground water and rocks and minerals (Kolodner et al., 2003). These examples are notable, but they comprise just a handful of units rather than the dozens that have been created to address physical science content. Furthermore, it is likely

that design challenges related to life science and earth science require even more scaffolding and direct instruction from the teacher if students are to make strong connections from their design endeavors to the science concepts.

*Trial and error methods and intuitive designing.* Even when science content and design challenges are naturally matched, children do not automatically construct scientific understanding as they complete a design challenge. The scientific content that seems evident to the teacher may not emerge at all for the students. One reason for this discrepancy is that if students are given enough time and materials, they can complete many engineering design problems through trial and error methods only. This approach to solving design problems may not be an effective tool to acquire knowledge about the related science concept. Another reason that science content may not emerge for students is that some design problems are solvable based only on prior knowledge of already existing artifacts. For example, students might design successful clay boats based on the shapes of large cruise ships they have seen in photographs. They are basing their design ideas on common sense rather than on scientific reasoning. This sort of intuitive designing can enable very successful solutions without any associated science knowledge construction (Fortus, 2003).

To deal with these threats to science learning, students' intuitive experiences with design and their trial and error discoveries must be articulated and formalized (Fortus, 2003). Teachers must plan thoughtfully for substantial reflection and discussion of *why* design artifacts succeed or fail. These activities must focus student's cognitive efforts on conceptual understanding rather than on task completion.

*Demands on teachers.* A third potential drawback to implementing design-based science units is the demands they necessarily place on teachers. With any instructional strategy, bringing

about change in students' science conceptions is a difficult task. When we add to that task the logistical hurdles of managing a classroom full of young designers and their materials, we create a job that is even more challenging. And while these logistical issues can be smoothed out with time and practice, design-based science presents yet another, even steeper challenge to teachers: facilitating lessons where there are always multiple "right answers" and multiple paths to arrive at each answer.

Many in-service elementary school teachers are products of a postsecondary education that required minimal coursework in science and typically no coursework in engineering or technological design (Tolman & Campbell, 1991). These traditionally educated teachers may be accustomed to treating science as a body of knowledge that contains one correct answer for any given question (Lederman, 1992; Tilgner, 1990). Without extensive support and better preparation in science, many in-service teachers may not be able to adapt their science teaching methods to activities that involve multiple acceptable solutions that cannot be anticipated ahead of time. These activities require teachers to have deeper science understanding as well as greater confidence in their ability to apply it to novel situations. After a class session in which each student has created a different artifact, achieving closure around a science concept requires the teacher to plan quickly how to apply her own in-depth science knowledge to the unpredictable creations of students, and then to transition students from physically manipulating materials to cognitively operating on ideas. These demands on the teacher cannot be overlooked. For some teachers that have attempted but not continued with design-based science instruction, these challenges are the main reason for the program's discontinuation (Kolodner et al., 2003).

*Sacrificing breadth for depth.* Educators who implement design-based science also struggle with the time constraints of the contemporary elementary school calendar. Many design-

based science units require a substantial time commitment: Roth's (1996) fourth/fifth-grade unit on structures lasted almost 40 hours! Although this is an extreme case, instruction that weaves back and forth between design endeavors and inquiry explorations does take longer than instruction aimed only on scientific inquiry or only on technological design. Integrating design and inquiry together is necessary for providing a deeper, richer set of experiences for children to draw upon when constructing science knowledge. However, this integration takes more classroom time, and there is a chance that fewer science concepts will be addressed in one academic year. The breadth of the science curriculum may need to be narrowed in order to increase its depth.

Though these challenges are significant, some design-based and project-based science units have been successfully implemented for several consecutive years (Kolodner, 2006; Krajcik & Blumenfeld, 2006). Such continued success suggests that the challenges are surmountable. More studies are certainly necessary, but the current state of research suggests that the potential benefits to student learning may make worthwhile the hardships associated with adopting design-based science curricula.

### *Section 6. Conclusion*

To report on the current state of design-based science instruction for children, I have synthesized cognitive theory, studies of instructional approaches, and research on professional engineering design. My key argument in this report is that engineering design may both *situate* and *distribute* children's learning about science. That is, engineering design may not only provide an authentic context for science investigation, but it may also enable the cognitive load of science investigations to be shared among a greater system. Within this system, a central role is played by student-constructed design artifacts. Researchers view the process of designing and building these artifacts as an engaging learning process (Kolodner et al., 2003; Krajcik & Blumenfeld, 2006), and they suggest that this process, as well as the completed constructions, is an external representation of students' knowledge (Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Olson, 2000; Roth, 1996; Vosniadou, Skopeliti, & Ikospentaki, 2005).

The work of this paper enables me to clarify my own definition of design as it pertains to elementary science classrooms. By *design*, I mean specifically a form of *engineering design*. As described earlier, I define engineering design generally as a conscious, deliberate activity of developing and testing a product (Benenson, 2001) that performs, under constraints, a specified and desired function for humans (Dym & Little, 2004) and that requires consideration of scientific principles and mathematical concepts (Bucciarelli, 1994). The activity of engineering design necessarily involves purposeful representations (Dym, 1994), which may include, among many possibilities, planning documents, preliminary sketches, mathematical computations, mathematical models of processes, models of scientific phenomena, explanation of relevant scientific principles, formal technical drawings, building instructions, and prose artifact descriptions.



To locate engineering design within the elementary science classroom, I must more specifically define *children's engineering design*. When children engage in engineering design, they need not produce all of the representations mentioned above, but they must engage in the act of representing at each major phase of design (Dym & Little, 2004): while conceptually planning, while building and testing details, and while communicating the solution. Children's final engineering design representations take the form of physical prototypes, which are tested against the requirements of the design problem (Benenson, 2001) and which are accompanied by writing, drawing, or speaking that would enable prototype replication (Dym, 1994). A student's prototype may be the actual solution to the design problem (i.e., a plastic bottle terrarium that will actually be used for a life sciences study) or only a functional model of it (i.e., a LEGO car that can climb a ramp, modeling a real car with the ability to climb hills) (Penner et al., 1998; Kolodner et al., 2003).

Cognitive theory and empirical research alike suggest that if children's engineering design is to set the stage for scientific exploration and deepened scientific understanding, then the construction of design artifacts must be accompanied by substantial representation and significant discourse. In other words, students must keep records, in written, drawn, spoken, or other representational form, as they plan, build, test, explain, share, and reflect upon their design artifacts. And teachers must help to establish a discourse of design in the classroom – shared ways of recording, discussing, and making sense.

To differing extents, both cognitive theory and empirical research lend support to the notion that design-like activities are an effective context for children's science learning. The theoretical basis for design-based science is more well-developed than the empirical basis. In this literature review, I have found that ideas from situated cognition theory, distributed cognition

theory, and engineering design theory can all be applied to the development of design-based science instruction.

Although the theoretical basis is stronger, the empirical basis for design-based science is also encouraging. Students who participate in design-based science instructional activities have shown improvement in science process skills, science discourse abilities, and engagement in science learning. However, the empirical basis does have some weaknesses, most significantly in three specific areas. First, there is a lack of evidence that design-based science brings about great conceptual change in individual students' science ideas. Second, there is a lack of evidence that a wide spectrum of teachers can overcome the unique demands of teaching science through science. Third, the empirical basis is comprised of a mixture of middle-school and elementary-school studies, and it is unknown if findings generated in middle-school classrooms can be extrapolated directly to the elementary school setting.

Nevertheless, the strong theoretical basis for design-based science, coupled with a weaker yet encouraging empirical basis, indicates that further research studies on design-based science for children would be productive. This research should focus on two areas. First, researchers and educators should work toward a set of curriculum development principles based on situated cognition theory, distributed cognition theory, engineering design theory, and lessons learned from prior studies of design-based science instruction. Second, researchers and educators should strive to incorporate such principles into design-based science curricula for upper elementary students, develop support mechanisms for teachers who implement the curricula, and examine how the enacted curricula impact students' science learning. Building upon the work of this literature review, such future research would continue to sharpen educators' ability to conceive of technological design problems that truly support children's science learning.

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