Developing the Field of Children's Engineering

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Abstract

Educational requirements for grades K-6 are increasing, students and teachers are being held to higher standards with inherent increased expectations learning. Because this is a time of change, the engineering profession has an opportunity to link with the K-6 science curriculum, complementing an existing science curriculum that finds itself challenged. Engineering also provides a contextual situation to reinforce important mathematical concepts**.** As the field of children's engineering (engineering for the K-6 grades) develops, it provides an opportunity to examine the fundamental tenets of engineering**.** This paper examines engineering at its most fundamental level, the level of understanding for 5 to 11 year-olds and demonstrates the importance of children's engineering.

I. Introduction

An increased emphasis on accountability for student learning from kindergarten to high school is occurring nationwide. State boards of education are requiring testing of children at various grade levels, starting in the elementary school. In New York State there are three standardardized tests given in fourth grade: one in mathematics, another in language arts and the third in science. The results in New York and in many parts of the country indicate that much needs to be accomplished, as student performance is not at the level expected for children living in the world's wealthiest country. Whether or not tests are a good measure of student knowledge and understanding in a subject area is debatable, but they are the assessment tool used. Student, teacher and district accountabilities are judged by these examinations.

If the curriculum and teaching methods were meeting the needs of students, assessments would be higher and questioning of educational methodologies would not merit much attention. This is a time of change, a time when administrators and teachers are seeking assistance, a time when traditional techniques are being questioned. This is a time when the engineering community can make substantial contributions to the K-6 educational program by introducing the concepts of engineering design and problem solving.

II. Educational Standards in Science and Mathematics

In New York and several other major states, the issue of standards was part of the 1980's reform movement that focused on increased graduation requirements (Ming Zu, 1996). This evolved into the reforms of the 1990's that were more pervasive, setting curriculum content standards as well as student performance standards. The aim is to improve students' critical thinking skills, not their test-taking skills. The New York State Board of Regents approved Mathematics, Science and Technology Education Learning Standards (MST) (1996) which set student performance indicators at elementary, middle and high school levels. This in turn has lead to the creation of assessment examinations to test competencies and understandings.

There are fundamental key ideas in each discipline that can be interpreted at different grade levels. For instance, in mathematics there are seven key ideas --mathematical reasoning, number and numeration, operations, modeling and multiple representation, measurement, uncertainty, and patterns and functions. For instance, students use mathematical modeling/multiple representation to provide a means of presenting, interpreting, communicating, and connecting mathematical information and relationships. They may demonstrate understanding by using concrete materials to model spatial relationships or to construct graphs and tables to display real-world data. In fourth grade mathematics, students must be able to read and interpret graphs and tables. Their ability might be assessed by providing a chart with information about planets and the lengths of a day in hours for each of them. Students would be asked to create a bar graph, appropriately labeled, for this information and then to discuss the data in written statement.

Students need to be able to measure in the metric and English systems, This provides them with a major link between the abstractions of mathematics and the real world in order to describe and compare objects and data. In this situation students use standard and nonstandard measurement tools to understand the attributes of area, length, capacity, weight, volume, time, temperature and angle.

The key ideas in science fall into two thematic groups--the physical setting and the living environment. In the former, the Earth and celestial phenomena are described by principles of relative motion and perspective, interaction between air, water and land on Earth observed, the particle nature of matter discerned, various forms of energy and energy interactions examined, and the interaction between energy and matter through forces that result in motion. For the latter, attributes of living things that are similar to and different from non-living things; genetic information in organisms, the evolution of organisms over time, the continuity of life sustained through reproduction and development, the dynamic equilibrium of organisms that sustains life, the dependency of plants and animals on their physical environment and the impact of human decisions on the environment. In New York State the fourth-grade science test has two parts, an objective test (multiple choice) and a laboratory assessment where students make observations and record data to reach conclusions.

The Benchmarks for Science Literacy (1993) is part of Project 2061, an effort to describe what science for all Americans should be, and it sets benchmarks for grades 2, 5, 8 and 12 in the following areas: the nature of science, the nature of mathematics, the nature of technology, the physical setting, the living environment, the human organism, human society, the designed world, the mathematical world, historical perspectives, common themes and habits of mind. The use of the word “technology” in the Benchmarks refers to engineering and at the K-6 level, also known as children’s engineering. The New York MST Learning Standards are closely linked to them,as many professionals collaborated on both projects.

For instance, in the benchmarks for the designed world indicate what students should know at the end of second grade:

> "Some kinds of materials are better than others for making any particular thing. Materials that are better in some ways (such as stronger or cheaper) may be worse in other ways (heavier or harder to cut);
>
> Several steps are usually involved in making things;
>
> Tools are used to help make things, and some things cannot be made at all without tools. Each kind of tool has its own special purpose;
>
> Some materials can be used over again" (1993, p. 188).

At the end of the fifth grade they should know that:

> "Through science and technology, a wide variety of materials that do not appear in nature at all have become available, ranging from steel to nylon to liquid crystals.
>
> Discarded products contribute to the problem of waste disposal. Sometimes it is possible to use the materials in them to make new products, but materials differ widely in the ease with which they can be recycled" (p. 188).

The National Council for the Teachers of Mathematics (NCTM) was the first to develop national standards with the Curriculum and Evaluation Standards for School Mathematics (1989). Several themes have emerged in terms of mathematical literacy (Steen, 1999, p. 12). These include use of ratio, percentage and proportion, geometric measurement in two and three dimensions, data analysis, estimation and approximation, argument and persuasion based on quantitative evidence. In the primary grades the emphasis is on the mathematics of whole numbers, common fractions and descriptive geometry (NCTM, 1989, p. 9).

The NCTM Standards (1989) seek to reform school mathematics, connecting to the twenty-first century. In the twenty-first[t] century business expects that employees will have the mathematical ability to set up problems, ask appropriate questions; use a variety of mathematical techniques (including the use of computers) in solving problems; and work cooperatively and collaboratively with others on these problems (p. 3).

The standards were created with the recognition that what a student learns depends to a great degree on how the material was learned (1989, p. 5). Was it learned in a drill situation? Was it contextually framed with need creating the desire for understanding? The belief system is that while some informational knowledge is useful, its real value lies in its application in a purposeful activity. This is consistent with the active-learning, constructivist instructional pedagogy employed in modern science education and in children’s engineering.

III. Fundamental Tenets of Science Education

In learning science, it is our hope that children will learn and understand scientific concepts, ideas, and scientific process--the how of science. A scientist may pose a hypothesis, e.g. for static equilibrium the sum of the forces and sum of the moments must be zero, which requires experimentation to prove or disprove. The scientist designs experiments, collects data, and makes observations of the data, through analysis, to confirm the hypothesis. The process of science requires understanding of concepts, not just memorization of ideas, for successful completion of investigations.

The constructivist view of learning is that “knowledge is actively constructed by the learner as he or she experiences the world" (Koch, 1999, p. 6). This is particularly important when one examines the work of Jean Piaget, who first recognized children’s numerous, and sequential, stages of cognitive development. The two that are important to the elementary school setting are the preoperational, ages 2-7 years, and concrete operations, ages 7-11 years. At the preoperational level children begin to see logical relationships, as they learn language and classify objects into groups, while at the level of concrete operations their thinking becomes more abstract, combining simpler categories into more general ones and applying these in mental operations. Other investigators have provided further insights to Piaget’s conceptualization of learning, arguing that the spiraling of the science curriculum allows students to build (construct) understandings at more sophisticated levels.

Children bring prior knowledge, which they created, or constructed, to the classroom. In constructing science experiences, teachers strive to make connections to students’ lives and to provide opportunities for active reflection about these experiences. Hands-on science without minds-on reflection and discussion does not allow for updating prior knowledge. Finding out about and having the student correct misconceptions is a vital part of science education. Children’s engineering provides synergistic ways to provide experiences through the engineering design process which imbed reflection and collaboration.

IV. Fundamentals of Engineering

Engineering predates science by millennia (Volti, 1995), as it is essential to our existence as humans. Humans would be a good food source for many animals if it were not for our creativity and intelligence applied to the development of artifacts to protect us. To include engineering at the K-6 level, one must answer the question, what are engineering fundamentals? What is engineering? *Webster’s College Dictionary* defines it as "the practical application of science and mathematics, as in the design and construction of machines, vehicles, structures, roads and systems." This definition belies the uniqueness of engineering, the body of thought it contains, and the methodology, uniquely its own, which it employs. Perhaps a more general definition would be a course of study followed by a professional life devoted to the creative solution of problems (Burghardt, 1999a). Engineering, in creating the human-made world, uses knowledge from science, mathematics, social science and humanities to solve problems. “Design engineers must grapple with environmental, legal, manufacturing, marketing, life cycle, intellectual property, cultural, and global considerations in creating their products and devices”

(Hales, 1999, p. 3). Otto and Wood (1999) point out that David A. Kolb's cyclic model of learning, consistent with Piaget's findings, involves concrete experiences, observation and reflection, conceptualization and theory, and active experimentation. Contextual-based learning is very effective, fostering understanding of conceptual ideas. There is a significant fit between engineering and the concepts and processes of science, pedagogically and in content areas.

The nature of engineering is to create, to solve problems of great variety subject to constraints and specifications. This is an output-driven discipline. The solution and the inputs will vary, utilizing the skills, knowledge and creativity of the designer. Parallel to science, engineering requires the application of ideas employed in the process of engineering. Children's engineering uses the engineering design process to create solutions. It uses the learning style advocated by Piaget and others to foster understanding of concepts. It engages students in active hands-on, minds-on activities that inherently contain reflection.

Engineers are creative problem solvers who do not seek unique solutions, but optimum ones, the kind in which trade-offs have been made between competing factors, e.g. time, money, and materials. There are several ways to describe the design process, but all include constraints and specifications, research and investigation, brainstorming and creativity, trade-offs and optimization, testing and evaluation, and analysis applied in an iterative, non-linear fashion. In engineering education it is important to assess the process as well as the solution, as our goals are both, not either or. This is exactly the case in children's engineering.

It is unfortunate that, in general, engineering has not been part of the K-12 educational system, a situation that at last can be corrected in this time of heightened expectations and educational need. There are movements in the United States and in several industrialized countries (Great Britain, Germany, Australia, Republic of China) to include engineering design and problem solving as part of the K-12 curriculum. This is often called technology education, the T in MST. Unfortunately, the phrase technology education was adopted just prior to the advent of personal computers, so instructional technology, essentially anything related to computers and electronics used in an educational setting, has been shortened to technology in most people's minds. Engineering is a better choice, with children's engineering being arguably the best choice at the K-6 level.

V. Children's Engineering

The elementary school day is a busy one, crowded with a variety of subjects that teachers must include a wide variety of curriculum requirements. Fitting the adage that assessment drives curriculum, standardized testing has the effect of teaching to the test, practicing fill-in-the-blank and multiple-choice examinations, further squeezing students and teachers. A ray of hope on the horizon regarding testing is that tests will become more opened-ended, permitting a variety of solutions, and may include laboratory portions. This is where children's engineering can be very useful, not as a separate discipline, but as a complementary one that provides the contextual learning so important to children and coordinating with the science and mathematics curricula.

Analysis plays a different role in children's engineering than it does in traditional engineering, while engineering design and the design process play similar pivotal roles. For millennia, analysis was not part of engineering; rather custom and craft formed the analytical base. For a children to design and fabricate a toy car, a model of a whale, a terrarium, it is not necessary that they know statics, dynamics, and strength of materials; rather that they consider the constraints and specifications of the problem statement and employ their knowledge and creativity. The analysis portion has it strongest links to science and mathematics; indeed that is a vital link between the disciplines. It is during this part of the design process, often when children reflect on their product’s performance, that they apply their knowledge of scientific principles and mathematical conceptualizations. For instance, they will understand force and friction when constructing, testing and evaluating axles; diameter and circumference when checking how far their vehicle moves.

Engineering links most closely with the physical sciences, but the elementary program predominantly focuses on life and earth sciences and the human body; so we must not only interconnect with the physical sciences, e.g. electricity, magnetism and simple machines, but also with living things, by designing models of ants and butterflies, homes for snails, rain forest plants and animals. In creating the models, students will need to understand and apply their knowledge of say, the rain forest, its structure and the various plants and animals that live at different levels. The design itself may require scaling a 150-foot tree to 15 inches, or an anthropoid from ten centimeters to thirty centimeters. "Skills required for mathematical reasoning are also fundamental to the design and construction process. Estimating, computing, using formulas are examples of skills that can be meaningfully incorporated in the planning and testing of a design" (Dunn and Larson, 1990, p. 28).

The design and analysis of the product, the artifact, are components in which only part of the learning occurs. It begins as the student researches the problem, journaling questions and insights along the way. An important mathematical concept design brings to the forefront is geometrical understanding. Visualizing in two and three space and making sketches and drawings are part of the design process. It is also an important part of elementary school mathematics.

The design can be guided through the use of a design portfolio. This is much more than a collection of student work; it provides a design process framework for the student as well as documenting key points of the process. The design project is developed to solve a problem whose genesis is often found in another area of the curriculum, such as reading, science, or social studies. This provides the context for the solution and creates a motivation for designing a device. Students in upper elementary are often required to write a short essay describing the context of their solution. Dunn and Larson (1990) point out that the design process fosters the interplay between reading and writing. In the research and investigation phase, children compare and contrast information from different sources, as well as writing in their portfolio’s daily log or journal. With every problem, in every design, there are constraints and specifications that further define the problem. As the designs evolve, these will be used to evaluate the acceptability of the solution. Burghardt (1999b) discusses an elementary school design portfolio and its assessment in detail.

The assessment includes whether or not the student solved the problem and met the constraints and specifications, as well as to how effectively the student completed and documented the process of design and verbalized understandings in the portfolio's conclusion and reflecting sections. The students' performance must convince us that they really understand material that quizzes and short-answer tests only suggest they understand (Wiggins and McTigue, 1998, p. 41).

Developing rubrics and supporting them with benchmarks is a very time-consuming process, in which the developer must think about what is valued, how that is demonstrated and how what is demonstrated can be quantitatively assessed. There is a rationale for each of these rubrics, evolved with much discussion and deliberation. The benchmarks received similar analysis.

A scoring scale, consistent with that used by the National Council of Teachers of English follows:

4--exceeding the level that you target in teaching
3--meeting the level you target in teaching
2--developing to the level you target in teaching
1--emerging

Sixteen rubrics and benchmarks for the design process, solution, communication and mathematics and science connections have been created. The rubrics that follow are used in assessing aspects of the design process and scientific inquiry (Burghardt, 1999b).

Explained problem and identified constraints and specifications.

4. Explained the problem in detail and from this context illustrated the necessary constraints and specifications.
3. Explained the problem in a few sentences, provided two constraints and two specifications.
2. Briefly explained the problem provided one constraint and one specification.
1. Did not explain the problem, provided no or only one total constraint and specification.

Provided conclusions based on the testing and made recommendations for improvements.

4. Analyzed the results from testing and made sense of them. Based on this made recommendations for design improvements and then modified the design and retested to show the benefit of the modifications.
3. Analyzed the results from testing and made sense of them. Based on this made recommendations for design improvements.
2. Analyzed the results and suggested design improvements but justification missing.
1. Did not reach conclusions from testing or recommend design modifications based on the testing.

VI. Conclusions

There are a variety of important reasons that indicate that including children's engineering is a valuable educational experience, one that enhances children's understanding of the natural world of science and the mathematical world of numbers and shapes. The connections to national learning standards in science and mathematics are direct. There is no need to displace curriculum or squeeze children's engineering into the school day; it fits nicely withinthe existing science program and has the added benefit of interconnecting with other areas of study, e.g. reading, writing, mathematics. The design process is inherently constructivist--it cannot be prescriptive and be design. It is the belief of many elementary school science educators that a constructivist learning environment is most effective, fitting with students' developmental learning styles. Elementary school teachers use a variety of assessment techniques. Children's engineering requires assessment strategies that look to understandings, not memorizations, which are important for developing the critical thinking and problem solving skills necessary in a variety of academic disciplines.

Major challenges are to alert the engineering and educational communities to the value of children's engineering, to demonstrate the performance of students learning in this environment, to link engineering faculty and elementary school faculty, and to provide enhancement to classroom teachers. Developing and teaching courses in children's engineering is exciting, rewarding and challenging.

Bibliography

AAAS. (1993). *Benchmarks for Science Literacy.* New York. Oxford University Press.

Burghardt, M. David (1999a). *Introduction to Engineering Design and Problem Solving.* New York: Mc-Graw Hill.

Burghardt, M. David (1999b). Assessing Elementary School Design Portfolios, *The Technology Teacher*, 59 (2).

Dunn, Susan and Larson, Rob (1990). *Design Technology—Children's Engineering*. New York: The Falmer Press.

Hales, Cripsin (1999). Design Perspective, *Mechanical Engineering Design*, 1 (1), p. 3.

Koch, Janice (1999). *Science Stories*. Boston: Houghton Mifflin Co.

Otto, Kevin N.and Wood, Kristin L. (1999). Designing the Design Course Sequence, *Mechanical Engineering Design*, 1 (1), pp. 39.

Ming, Zu (1996). Will Raising Standards Improve Student Achievement? NYS Education Department, Albany, NY. www.nysed.gov/rscs/rschstds.

National Council of Teachers of Mathematics (NCTM) (1989). *Curriculum and evaluation learning standards for school mathematics*. www.enc.reform/fworks.

New York State Learning Standards for Mathematics, Science and Technology (1996). State Education Department. Albany, New York.

Steen, Lynn Arthur (1999). Numeracy the New Literacy for a Data Drenched Society, *Educational Leadership*, Oct.

Volti, Rudi (1995). *Society and Technological Change 3rd edition*. New York: St. Martin's Press.

Wiggins, Grant and McTighe, Jay (1998). *Understanding by Design*. Association for Supervision and Curriculum.

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