Problem-based Learning for K-12 Engineering

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Abstract - **There is increasing support and funding in the United States for developing and testing K-12 curricula that engages students in science, technology, engineering, and mathematics (STEM). As a primary result of this support, numerous curriculum development projects have been implemented to develop K-12 engineering and technology programs. Some of these curriculum projects deliver engineering-related content to secondary (K-12) students in a manner that is somewhat reflective of methodologies used in post secondary (university) instruction. Other K-12 curriculum projects are experimenting with alternative instructional design methodologies. This paper provides a rationale for additional curriculum experimentation, an overview of five contemporary K-12 curriculum projects underway in the U.S., as well as the instructional design methodologies and curriculum priorities unique to each. The paper concludes by elaborating on the results of pilot- and field-tests of the National Science Foundation supported Project ProBase. The ProBase curriculum is a problem-centered constructivist curriculum that uses engaging design problems to deliver engineering and technology content.**

Index Terms - K-12 engineering, problem-based curriculum, secondary education, technological literacy, technology education.

THE STATE OF STEM

Experts from across the United States have warned of an impending national crisis in the fields of science, technology, engineering, and mathematics (STEM). Just as the nation's economic engines and national security measures have come to rest squarely on the shoulders of the STEM fields, secondary and post secondary students are turning away from science, technology, engineering, and mathematics in record numbers [1]. The National Science Foundation [2] reported that the United States is experiencing a chronic decline in homegrown talent and is increasingly dependant upon foreign scholars to fill workforce and leadership voids. University student admissions to some post secondary STEM programs are down as much as 33 percent over previous levels [3]. Meanwhile, a recent report from the U.S. Bureau of Labor Statistics [4] predicts that the number of jobs in STEM occupations will grow by 47 percent—three times the rate of all other occupations by the year 2010. If nothing is done, this shortfall will force U.S. employers to look overseas for talent in the most promising occupational fields [5]. To reverse this trend and enlarge the domestic talent pool of interested and qualified students in the STEM fields, K-12 STEM curriculum materials and instructional strategies must identified, tested and implemented [1]. We must also develop and implement curriculum demonstration projects in K-12 education that promote engaged and hands-on learning in the STEM fields—particularly engineering.

EXPECTATIONS OF PUBLIC EDUCATION

The continual global march of technology has heightened the expectations many hold for public education. No longer are the fundamental reading, writing and arithmetic enough to satisfy most with the local secondary school [1]. The public demands a more savvy citizenry—a graduate with the skills to solve complex technological problems, competence with computers, an ability to manage and make sense of large amounts of data and information, and an ability to work in diverse settings to solve increasingly complex problems. Since these are skills that are typically associated with the practice of engineering, there is an increasing level of interest in introducing engineering to students at the pre-college level [6]. This reasoning suggests that student interest in engineering may be piqued by providing them with engaging experiences at an early, pre-college age. Subsequently, engineering courses and programs are beginning to emerge in secondary schools in almost every part of the United States, particularly where state initiatives have placed a high emphasis on technology, or on boosting the number of qualified engineers [7]. This emergence seems to be driven by both advocates internal and external to the engineering community. There is widespread belief within the engineering community in the United States that secondary-level curriculum materials development and implementation is a powerful way to affect the number and quality of students entering post secondary engineering programs [8, 9, 10].

Unfortunately—with some notable exceptions, teacher training programs in the U.S. do not prepare secondary STEM teachers with the motivation, content, or methodology that enable them to prepare their students for continuing post secondary education in engineering and technology. It follows that better preparation of secondary STEM teachers and a heightened exposure to high quality engineering and technology curriculum materials and instructional methodologies are required [11]. Movements toward a changed curriculum in teacher education are evident in selected programs across the United States. The restructuring of STEM teacher education has involved an examination of both the academic content needed and the unique experiences chosen for integration into a preparation program. Nowhere is this more evident than in the technology teacher education programs across the United States. With the publication of the *Standards for Technological Literacy* [12] many leaders in technology education have reexamined the essence and purpose of their programs and have established goals and practice that when carried out will assist them in developing a secondary teacher able to deliver engaging content closely tied to engineering education. Yet, as with all educational reformation, this will not satisfy our immediate needs for vast increases in the rates of students entering into and journeying through the engineering pipeline. The more immediate fix is through curriculum experimentation, development, and augmentation as well as the delivery of professional development programs for practicing secondary teachers.

A CALL FOR CURRICULUM

In an October 2005 presentation titled, Rising above the gathering storm: Energizing and employing America for a brighter economic future, P. Roy Vagelos, retired chairman and CEO of Merck & Co., Inc. testified before a the Committee on Science of the U.S. House of Representatives that his committee proposed that high-quality STEM teaching be fostered with world-class curricula, standards, and assessments of student learning [13]. He further recommended that U.S. Department of Education convene a national panel to collect, evaluate, and develop rigorous K–12 materials that would be available free of charge as a voluntary national curriculum [13]. While it is unclear at this stage whether the U.S. Department of Education has begun to collect or evaluate any curriculum materials, the materials are clearly being developed under the auspices of numerous state and federal agencies, private foundations, university initiatives and association taskforces [1, 14].

These curriculum materials, software packages, instructional activities, and other technology-based materials are emerging as alternatives to the traditional textbook and as legitimate teaching material and content for pre-college students in science, technology, engineering, and mathematics classes. In many cases, these innovative new materials provide students with engaging activities and applied explorations of engineering content that was largely missing from the secondary school only a few short years ago [14]. For secondary teachers, these new curriculum materials provide opportunities to expand their knowledge of basic STEM concepts and their teaching repertoire to include more engaging methodologies [15].

While the impetus for the creation of these new curriculum materials seems largely driven by concern about shortages of entering post secondary STEM students, the relative value of existing curriculum materials (i.e., textbooks) in mathematics and science seems of equal concern. Findings from cognitive science researchers like Bransford, Brown, and Cocking [16] as well as leaders in the curriculum design community like Wiggins and McTighe [17] offer suggestions for the creation of more effective curriculum materials as well as criticism for the wide use of existing textbooks. Frankly, there is a growing concern and evidence that traditional secondary-level textbooks do not adequately prepare students for post secondary educational experiences. This is particularly true when one considers subject area content not traditionally incorporated into secondary textbooks—like engineering and technology. Supporting this notion, a study funded by Project 2061 of the American Association for the Advancement of Science [18] found that none of the major textbook publishers provided a coherent approach to the content or adequate instructional support for teachers during an assessment of secondary science textbooks. Additionally, many traditional textbooks are criticized for not making use of new learning technologies or innovative instructional strategies [19]. Hence, new secondary-level instructional materials are largely being developed outside the margins of traditional textbook publishers in funded curriculum projects, through association task forces, and in private foundations. All of these venues seem to offer more flexible and responsive approaches to contemporary secondary STEM curriculum development

CURRICULUM PROJECTS

Numerous K-12 engineering curriculum projects have been launched in the United States in the last decade. Some of these projects have been supported by professional associations, universities, and private foundations while others have been funded by governmental agencies. A few notable projects will be outlined in the paragraphs to follow.

I. Project Lead the Way

Project lead the Way (PLTW) is a privately funded secondary engineering curriculum project. PLTW has developed a four-year sequence of courses which, when taught in conjunction with college preparatory mathematics and science courses in high school, is designed to introduces students to engineering and engineering technology content prior to entering college [20]. These courses include:

- Introduction to Engineering Design
- Digital Electronics
- Principles of Engineering
- Computer Integrated Manufacturing
- Civil Engineering and Architecture
- Biotechnical Engineering (in development)
- Aerospace Engineering (in development)
- Engineering Design and Development

Together, these eight courses are designed to attract more students to engineering, and allow students, while still in high school, to determine if engineering is the career they desire. The Project Lead the Way program is probably best known for its teacher training model. Practicing teachers who elect to initiate a PLTW curriculum in their school must participate in summer training workshops at participating university sites.

II. TECH-know Project

TECH-know is a National Science Foundation-funded project designed to create technology-based curriculum problems that support and expand upon competitive events sponsored by the national Technology Student Association [21]. The curriculum materials in development will include problems covering a wide variety of topics in construction, communication, manufacturing, and transportation technology. The materials will be based upon fundamental science, mathematics, and technology concepts as well as the national standards from each of these disciplinary areas. The projected outcomes of the TECH-know project include:

- The publication of high quality instructional materials that enhance the development of fundamental science, mathematics, and technology knowledge;
- The development of student creativity and critical thinking skills related to science, mathematics, and technology through the application of problem-based, inquiry-guided pedagogy; and,
- Positive student attitudes toward science, technology, engineering, and mathematics.

III. Engineering the Future

Engineering the Future is a full year, secondary-level engineering course developed at Boston's Museum of Science. The course provides a foundation in physics and offers students an opportunity to explore the social, historical, and environmental contexts of emerging technologies [22]. A central goal of the course is to build technological literacy for every student. Throughout the course, students develop a practical understanding of how they are influenced by technology, and how they influence future technological development by the choices made. The curriculum materials include:

- A textbook of first person accounts from a variety of technicians and engineers;
- An engineering notebook for students to use as they complete hands-on projects, science and math practices; and,
- A teacher's curriculum guide.

The curriculum was originally pilot-tested in 2005 and is undergoing additional testing in 80 Massachusetts schools during the 2005-2006 school year.

IV. VisTE

VisTE (Visualization, Science, and Technology) is a National Science Foundation funded project, which promotes technological literacy among high school students through the study of visualization, science, and technology [23]. The project is developing and testing 12 curriculum units for grades 8-12. These curriculum units are designed to promote the effective use of graphics to communicate scientific and technical information while supporting conceptual and theoretical problem solving through an inquiry-driven engineering design format. The curriculum units will be based upon secondary national standards in science, technology, and mathematics. The units under development and testing include:

- Principles of visualization skills;
- Agricultural and related biotechnologies;
- Medical technologies;
- Transportation technologies; and,
- Information and communication technologies.

V. Project ProBase

After four-years of development under National Science Foundation support, the Project ProBase curriculum was released in March of 2006. The ProBase curriculum is an engineering design problem-centered curriculum intended as a capstone experience during the last two years of high school. The core competencies for the curriculum are delivered through the implementation of engineering design problems that engage students in technological design, invention, innovation, troubleshooting techniques, experimentation, and research and development. The curriculum consists of eight, 9-week learning units grounded in standards-based content, and delivered through technological problem-solving activities. The concept-rich curriculum provides a comprehensive foundation of technological knowledge and skills needed to "bridge" students to engineering and post secondary technical degree programs [14]. The eight, 9-week learning units include:

- Transportation Technologies;
- Information and Communication Technologies;
- Energy and Power Technologies;
- Manufacturing Technologies;
- Construction Technologies;
- Medical Technologies;
- Agriculture and Related Biotechnologies; and,
- Entertainment and Recreation Technologies.

In addition to the five programs briefly outlined above, a quick Internet search identified numerous additional projects that merit further research and investigation. A small sample of these projects is listed below:

- Project SEED: The American Chemical Society
- Detroit Area Pre-College Engineering Program (DAPCEP)
- Engineering is Elementary
- Gateway to Higher Education
- El Paso Collaborative for Academic Excellence (EPCAE)
- Mathematics, Engineering, Science Achievement (MESA)
- Texas Pre-freshman Engineering Program (TexPrep)

A CLOSER VIEW – THE PROBASE CURRICULUM

The ProBase curriculum differs from most of the other curricular approaches in that it attempts to deliver standards based content [12] utilizing both a problem-centered curriculum, and a backwards curriculum design model. Wiggins and McTighe's backwards curriculum design [17] involves identifying assessment and curricular expectations prior to developing any instructional materials.

I. The Conceptual Foundation

Probase curriculum development was initiated by distilling nine *enduring understandings* and related essential questions from the Standards for Technological Literacy [12]. The term "enduring understandings" refers to the big ideas, the important understandings that we want students to own after they've forgotten much of the day-to-day trivia of the classroom [17]. Before being identified as one of the nine enduring understandings for the curriculum, each concept had to filter through four questions:

- Is the concept something important to know as an adult?
- Is the concept important in the fields of technology and engineering?
- Is the concept an abstract or an easily misunderstood idea?
- Can the concept potentially engage students in the study of technology and engineering? [17]

Upon passing through these filters, each enduring understanding was then further clarified through the use of essential questions—questions that one would reasonably expect a competent student to be able to answer after having successfully completed the lesson or a unit of instruction in the ProBase curriculum.

The second conceptual foundation for Project ProBase consisted of a set of bridge competencies, designed to bridge the gaps between secondary and post-secondary education. The Project first identified the base-level competencies required in engineering or technician-level post secondary education. Through a series of focus group sessions, with post secondary educators a set of six Bridge Competency categories were compiled. These categories are: academic, communicative, computer, logic, social, and technical competencies. Through the use of a concept matrix, the curriculum materials were continuously monitored for bridge content throughout the developmental process.

II. The ProBase Learning Units

The conceptual foundations of backwards design and bridge competencies undergird the curriculum framework utilized in the ProBase curriculum. The ProBase curriculum consists of eight learning units. Each of these learning units is delivered utilizing a set of technological and engineering design problem solving activities. Each of the eight learning units consists of 40 hours of instructional time, approximately 9-weeks, and may be offered on a nine week, one-semester, or one-year basis. While completing each of the eight learning units, student teams are challenged to solve *Primary* and *secondary* engineering design problems by conducting research, gathering information, asking technical questions, and studying core technological concepts or engineering heuristics.

At the beginning of each learning unit, students are engaged in a "hook" activity, called the *Preliminary Challenge*. These hands-on activities are designed to pique student interest and establish a focus for the curricular unit. Students are then introduced to the unit's *Primary Challenge*, which is a complex problem designed to initially exceed the competence levels of most secondary students and to engage students with the unit's enduring concepts and essential questions. For example, in the Energy and Power Technologies learning unit, the *Primary Challenge* requires students to build and operate a portable, light-weight hydroelectric generator capable of operating at established limits.

Following this introduction, students work in cooperative teams to progress through core concepts, conduct research, solve secondary-level design problems, and implement technological assessment techniques in the effort to develop a solution to the *Primary Challenge*. This conceptual and skill development is constructed using a learning cycle strategy. Each learning cycle focuses on two or fewer enduring understandings and builds student knowledge of them through four phases of learning, called Exploration, Reflection, Engagement, and Expansion.

- In the Exploration Phase, students explore concepts, interact with materials, collect and record data, and make predictions. For example, in one learning cycle of the Transportation Technologies learning unit, students explore the concept of propulsion through torque and gear ratios. Students begin the learning cycle by investigating what torque is and how it is measured and proceed to construct an apparatus that allows them to test and measure the amount of torque needed to hold a weight of 1000 grams at various centimeter increments along a given lever arm [14].

- The Reflection Phase of the learning cycle requires students to reflect on the exploration and answer questions related to a particular concept. This stage often includes a concept-focused class discussion. Building on the same example from above, students might answer and discuss questions such as "Why did the lever arm become difficult to hold at the weight moved farther from the person holding it?" or "What would the torque be at the 90 cm point of the lever arm?" Students also reflect back on their experiences of exploring gear ratios.

- During the following Engagement Phase, students apply knowledge gained in the Exploration to solve a problem (usually unrelated to the Primary Challenge). For example, in the learning cycle related to torque students apply their knowledge about torque and gear ratios by designing and constructing a vehicle that pulls with the greatest possible force.

- Finally, the Expansion Phase of the learning cycle causes students to expand concepts and generalized to broader situations. This section often requires students to conduct reading and research to draw conclusions about the concepts. Returning to the example, students have the option of setting up an experiment to test the torque produced by a bicycle, prepare a presentation on torque and gear ratios suitable for a hypothetical middle school class, or to find a discarded device with gears and, through reverse engineering, determine why gears may have been used and what gear ratios were used.

The end of the Expansion phase takes students back to the Primary Challenge and allows them to apply this newly gained knowledge directly to that challenge, and answer the question, "What have we learned in this learning cycle that can help us solve the Primary Challenge?" In this case, students have learned about propulsion, torque, and gear ratios, and can use this knowledge to help them solve the Primary Challenge for the Transportation Technologies unit, which in general terms consists of designing and constructing a small vehicle capable of transporting cargo in a specified destination.

III. Pilot and Field-Testing

After initial development and substantial refinement, each learning unit was subjected to a rigorous pilot and field-testing process at selected schools across the United States. These pilot- and field-testing locations consisted of upper-level high school technology education classes. The schools participating in the pilot- and field-test were selected based on their ability to provide the project with a demographic important to the project. For example, schools were selected based on type, ethnic diversity, socio-economic make-up, racial diversity, population density, and other factors. In general, results from the pilot- and field-test indicated that the materials:

- Conceptually challenged students as they encountered concepts that they had not previously addressed or unfamiliar concepts integrated from other disciplines;
- Engaged students in design activity and design teams that required both individual ability and the ability to work as a member of a team;
- Required additional preparation time and laboratory set-up time for instructors as many of the lessons and experiments were unfamiliar and new;
- Challenged the instructors to remain conceptually ahead of the students;
- Challenged the instructors to utilize performance—based assessment tools in addition to more traditional methods of student assessment.

Based on the results of curriculum testing at the pilot-sites, recommendations from curriculum writers and editors, and reviews from project directors, the project steering panel and external evaluator, revisions were made and additional field-tests were completed at additional schools. The final version of this curriculum was released to the public in March, 2006.

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CONCLUSIONS

The need for innovative curriculum development, demonstration, and implementation in K-12 engineering in the United States is strong. There are numerous curriculum development efforts underway—each with their own goals, strategies, and purposes. Some of these curricular approaches may be more effective, more popular, or more widely applied than others. However, in light of their differences in content and methodology, and instructional approach, all of these curriculum projects represent a national recognition that STEM education must be addressed at the secondary level and K-12 students must be provided with educational experiences that both heighten their awareness of engineering potentialities and engage them in content that will make a future in engineering more likely.

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