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Engineering & STEM: Complementary Areas of Study*

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Many K-12 educators approach STEM disciplines as if each one (Science, Technology, Engineering, and Mathematics) exist in isolation from each other integrate the content and skills of the disciplines that can engage students on many levels. STEM education is meant to be an interdisciplinary area of study that integrates the four disciplines rather than achieving skills and knowledge independently in each subject area. This paper examines the several attempts to define STEM and discusses the basics and issues related to the implementation of STEM programs and how engineering is a suitable vehicle for development and implementation of STEM programs, whether the focus of the course is science, technology, engineering, or mathematics. The value of the Next Generation Science Standards in this endeavor will be detailed. In addition, the paper will examine the relevance of STEM Career Technical Education (CTE) programs.

Keywords: STEM implementation; interdisciplinary approach; Next Generation Science Standards; curricula integration; K-12 education

1. Introduction

STEM is an acronym for Science, Technology, Engineering and Math, that has become a significant aspect of K-12 educational reform in classroom practice and curriculum reform, as well as in workforce development. The significance of STEM education lies in the skills and knowledge in each discipline because these fields are very connected in the real world. However, "STEM Education" is being defined in many ways by different groups, as K-12 educators seek to "implement STEM programs" in their schools, so that defining and implementing STEM courses and programs have become a confusing effort and a challenge to the K-12 education sector [1–3].

Many K-12 educators approach STEM disciplines as if each one (Science, Technology, Engineering, and Mathematics) exist in isolation from each other. Alternately, they may believe that an engineering experience and/or robotics can be considered a STEM program, even if an engineering problem involves only doing some arithmetic or a scientific concept which is not explored in the activity [4]. The distinction between technology education and educational technology is also an area of confusion lies in the matter. For those in educational technology, there is the view that the "T" (for technology) means only the use of technology for education purposes such as the use of computers as opposed to educating students on various technologies, their development, and their application.

STEM education is meant to be an interdisciplinary area of study that integrates the four disciplines rather than achieving skills and knowledge independently in each subject area. A STEM program should integrate the content and skills of the disciplines that can engage students on many levels, as well as provide students experiences in problem-solving, analytical, and communication skills. Thus, STEM programs should be an interdisciplinary and applied approach that is coupled with hands-on, problem-based learning. As a result, a student should possess the ability to apply understanding of how the world works within and across the disciplines of science, technology, engineering and math.

As engineering focuses on the mathematical and scientific principles related to problems and solutions, the Next Generation Science Standards (NGSS) [5] becomes an excellent vehicle for implementing K-12 STEM programs and courses, as it provides guidance for effective STEM education across the K-12 grade levels. NGSS is meant to provide educators a road map for how prepare their students to apply quantitative tools that are applied in a variety of contexts in Science and Engineering Practices. NGSS is also aligned with the Common Core State Standards in Mathematics (CCSS-M) [6].

This paper discusses the several issues related to the implementation of STEM programs and how engineering is a suitable vehicle for development and implementation of STEM programs, whether the focus of the course is science, technology, engineering, or mathematics. The value of the Next Generation Science Standards in this endeavor will be discussed. In addition, the paper will examine the development of Career Technical Education

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(CTE) programs as an approach to prepare students for post-secondary education and/or the STEM workforce.

2. Implementation of STEM

We have taken the view that the development of an academic program and/or courses for a branch of learning such as STEM should encompass the three distinct, but interrelated components of teaching and learning:

INSTRUCTION: How should we teach?
CURRICULUM: What should we teach?
ASSESSMENT: How should we measure student learning?

All interrelated activities can be described in lesson plans that are designed to align the three components into a coherent process, by defining EXPECTATIONS of student learning, CURRICULUM & INSTRUCTION for students to have opportunities to learn, and ASSESSMENT for MEASURING the extent of student learning. Specification of learning objectives allows the alignment of classroom instruction with performance expectations conveyed in the NGSS document.

2.1 Instruction

Even though the advent of Next Generation Science Standards has led to a strong push for effective K-12 STEM education across K-12, there is still great confusion among K-12 educators as to how to effectively represent the "E" in "STEM." Implementation of STEM programs must address the problem that relatively few K-12 teachers can focus on the engineering concepts and practices because few of them are equipped to do so. Many K-12 teachers have not been trained to incorporate STEM, especially engineering topics into their programs. Teachers may lack that certain set of skills and knowledge to begin integrating technology and engineering concepts into their classroom practices. A report on a survey that explored current teacher perceptions of STEM education concluded that: STEM education is not well understood; and there is not a clear vision of STEM education even amongst those who believe it is important [7].

Comprehensive professional development programs are needed for teachers to acquire new skills and knowledge so that they are able to integrate technology and engineering concepts into their classroom practice. They must learn how engineering focuses on the mathematical and scientific principles related to the engineering problem and solution. The recent release of "Standards for the Preparation and Professional Development for Teachers of Engineering" will provide guidance for professional development providers.

The planning of professional development programs that lead to desired teaching practices is not a simple process. Professional development for teachers is considered a key vehicle for educational reform and the need for improving classroom instructional practice and student achievement [8–12]. Too often, short term teacher training institutes and after school workshops are seen as ends in themselves. These "one shot" approaches to staff development may fail to result in lasting changes in teaching behavior because teachers are not provided with the opportunity to experience success. Teachers are not likely to change their classroom instructional behavior unless they are given the skills, knowledge, and confidence to do so.

A report of the Council of Chief State School Officers (CCSSO) [12] provides a set of the features that influence effective professional development outcomes: three core features (active learning, coherence, and content), and two structural features (duration, and collective participation): (a) *Active Learning*: Teachers are involved in discussion, planning, and practice; (b) *Coherence*: Activities are built on prior student knowledge and will lead to more advanced work; (c) *Content Focus*: Content is designed to improve/enhance teachers' knowledge and skills; (d) *Duration*: Professional development for teachers extends over at least a two-year period; and (e) *Collective Participation*: Teachers are encouraged to meet in discipline and grade level groups to discuss strategies and content, and share approaches they develop with peers.

Professional development is integral to increasing teachers knowledge and skills, and to learning effective application of the skills in the classroom in order to meet the needs of all learners. The goals for the implementation of teacher professional development programs should be to enhance teachers' skills and knowledge, improve their classroom practice(s) and increase student learning. How to accomplish these goals within the context of the existing curricula that are aligned with the skills and knowledge specified by content standards is also a very important issue.

While there has been recognition of the professional development needs of current teachers, very little attention has been paid to the next generation of teachers coming out of teacher preparation programs. A major problem is that most, what is referred to as STEM teachers, are trained in either science or mathematics, and may not be trained in engineering and technology. Currently, there appear to be very few teacher preparation programs that are training teachers in instructional strategies for integrated instruction. Further, very few states have STEM teacher certification. Teachers are certified in one of the individual subjects of STEM. Yet, considering the amount of content and pedagogical knowledge necessary to prepare an effective, science, math, or pre-engineering/technology teacher, it is difficult to imagine a new pre-service teaching/licensure program that could prepare teachers with the necessary STEM content and pedagogical expertise to teach all these bodies of knowledge effectively. At some universities, schools of education are partnering with engineering departments to provide graduate programs for science and math teachers to meet these challenges [4]. This is an issue that requires immediate attention.

2.2 Curriculum

What does it mean when a school or district announces that they are developing a STEM curriculum?

The integration of the subject areas of STEM is difficult to do. Instructional materials that utilize engineering design are very limited. There is a low emphasis on integrating mathematics and science in current pre-engineering classes and assessments of student projects. The results of one study suggests that while some of the available pre-engineering curriculums are meant to provide learning experiences in math and science embedded in the engineering activities, they do not [13]. Other curriculums depend on students taking the math and science courses in parallel with the pre-engineering courses.

Many existing curricula that resulted from NSF funded projects are considered "exemplars of engineering curricula. But are they to be considered as interdisciplinary STEM curricula? For example, according to the introductory material for one of the curricula, it assumes that students are studying or have already been studied the science concepts that are being utilized in the engineering lessons [14]. The relevant science concepts may be simply reviewed or referred to in the course. In another engineering curriculum, there is no listing or specification to either science or mathematics concepts, only references to them. These curricula would not fit the definition of interdisciplinary nature of what STEM programs should be. STEM curricula should include the integration of instruction and learning experiences for the different STEM areas in a given curriculum.

One study found that students would use a trial and error approach with a malfunctioning device rather than using a systematic approach to solving the problem, such as using mathematical models to predict possible solutions [15]. This would not be consistent with the practices of engineering specified by NGSS, which has the expectation that students would do more than simply build and test devices. The four areas of STEM share commonalities [16]. Problem-solving is a major focus of curriculum and instruction for these subject areas, although the terminology is used differently for each subject. In addition, systems and models are a common theme among these subjects. Each subject may use these terms differently, but they serve the same purpose of representing relationships, and the relationship between parts and the whole system. Curriculum materials are needed that embed mathematical problems and science inquiry activities into the engineering process are needed.

Curricula should provide the primary connections between instruction and learning as well as the link between standards and assessment of student learning. The Next Generation Science Standards provide student performance expectations, specifying what students should know and be able to do. These standards are *not* meant to be curriculum. NGSS identify eight practices in science and engineering that are meant to serve as starting points for the integration of engineering, science and mathematics. The NGSS explicitly includes practices and concepts from engineering as parallel with those for science, while providing links to mathematical concepts, including modeling and computational thinking, with the expectation that science teachers would teach science and engineering in an integrated fashion.

Two approaches have been previously described [17].

- Implementation of an "engineering track" such as an "engineering/engineering technology program". This approach would usually begin with an introduction to engineering and engineering design, followed by some sequence of modules/courses focusing on different areas of engineering. Appropriate science and mathematics concepts would .be included explicitly in the engineering lessons of the course, and included in the assessment of student learning. While prepared pre-engineering programs are available, many teachers find them expensive and usually do not allow the teachers any flexibility in the implementation. Thus, many teachers prefer to develop and implement their own curriculums, some of which are reported in the literature [18–22].

  At this point, the distinction between technology (and engineering technology) and engineering should be clarified. Any discussion of technology and engineering literacy must include a clear idea of exactly what technology and engineering literacy means. The difference between Engineering Technology and Engineering lies in the hands-on approach to teaching in Engineering Technology, vs. a more theoretical approach in engineering. Faculty in an Engineering Technology program tends to have many years of industrial experience, as opposed to post-doctoral experience for engineering faculty. Most courses in Engineering Technology have a laboratory component to enhance classroom instruction. Support courses, such as math and physics, tend to be taught in a more applied manner than in engineering programs.

- Integration of engineering principles and appropriate applications into the science and mathematics courses offered by the school. In this approach, students should be able to see the parallel nature of the engineering design process, the scientific inquiry process, and mathematical problem solving.

  Use robotics to integrate engineering principles and appropriate applications into the science and mathematics courses offered by the school. Here, students can see the parallel nature of the engineering design process, scientific inquiry process, and mathematical problem solving. Robotics has been shown to be an excellent vehicle for the integration of engineering with scientific principles and math concepts [23–27].

Another suggested pathway has been Career and Technology Education (CTE) programs, as a means to support an integrated STEM program [28, 29]. Thus, in a program for manufacturing technology, students could learn mathematics and science in the context of issues they might encounter in an actual manufacturing facility. For example, students could work on projects that involve designing robots that could automate some processes occurring in a factory.

2.3 Assessment

Assessments properly integrated into instruction, can provide valuable information about progress towards instructional goals, and overall curriculum implementation. Most assessment at the K-12 level is summative, i.e. at the end of a chapter or marking period, end-of-course exams, yearly state-wide assessments, etc. Assessments should be formative. Gather data as the learning occurs and modify those learning strategies implemented in the instruction and/or developed in the curriculum that are not effective in student mastery. Assessment before, during (formative), and after (summative) a lesson or series of lessons is necessary to demonstrate that each student is acquiring targeted skills and knowledge. Students may demonstrate proficiency in some areas, but may not understand a concept in a different area. Formative assessment can identify this problem area and provide critical information to select a vehicle for helping the individual student.

Outcomes for some learning objectives can be difficult to measure. STEM literacy is a case in point. Because it has not yet been well defined and because it includes many different elements (30), measuring STEM literacy as an outcome of a particular integrated educational experience can be problematic. However, individual aspects of STEM literacy should be measurable outcomes; for example, understanding of specific science or mathematics concepts or awareness of how the STEM disciplines help shape our world. Outcomes are usually determined through standard measures of achievement or gauged through formative or summative tests designed to measure learning related to a specific curriculum, course sequence, or activity.

Research on the impact of integrated STEM experiences on students' achievement, disciplinary knowledge, and ability to make connections between subjects is limited [31]. However, preliminary studies suggest that integration can lead to improved learning of concepts in the disciplines. But the effects differ, depending on the nature of the integration, and the outcomes measured, as well as the students' prior knowledge and experience. Most studies of STEM learning consider each discipline individually and do not measure students' ability to make connections between disciplines. In addition, learning is often assessed using standardized achievement tests, which may not effectively measure the full range of learning from integrated experiences. Few assessment instruments on integration are available because theories and tests have generally focused on content area—specific concepts and procedures and no widely accepted definition of integrative learning is available. A recent report attempted to measure student learning outcomes from a STEM program [32]. But a pre- and post- end-of-program assessment of learning was used, which makes it difficult to measure outcomes from specific lessons or activities. And as an end-of-program assessment, the degree of learning for this study was not reflected in the assessment scores.

Standards-based lesson plans require a different way of planning that includes: an alignment of student work expectations and classroom assessments to the standards; the learning objectives and expected outcomes of the lesson; and the establishment of criteria by which it can be determined whether students have achieved the particular standard or indicator. Standards-based lessons use measurable learning objectives to assess student actions or evidence of mastery through their work products. Alignment of a lesson with instruction requires that standards be bridged with desired student outcomes specified by grade appropriate indicators of the standards. A working protocol for the creation, implementation, and assessment of standards-based lesson plans has been created, and professional development programs have been developed by the Center to train teachers how to utilize the established protocol [33, 34]. The protocol includes:

(1) Identification of measurable student-focused learning objectives.
(2) Specification of the expected progress indicator from the corresponding content standards statement for each learning objective.
(3) Development/adaptation of a learning experience (activity) that provides the student with the opportunity to acquire the skill and/or knowledge specified by the learning objective.
(4) Description of the expected student learning outcome/performance that provides the evidence that the student has acquired the skill and/or knowledge. The description of the expected student learning outcome/performance is used to analyze student behaviors and mastery through work products, which provide evidence that the student has acquired the skill and/or knowledge of the learning objective specified by the indicator(s) of the standard(s).

The process for standards-based lesson planning allows teachers to systematically assess learning outcomes that are aligned with state and national content standards. Just as important is the need to gauge the quality of a lesson plan by how well the learning objectives and standards are being met. We have developed a rubric to provide a measure of the effectiveness of standards-aligned lesson plans which focuses on the criteria that identify and measure the parameters of a standards-based lesson plan [34].

3. Discussion

As described in this paper, many now recognize STEM education as in interdisciplinary approach to learning that interconnects STEM-related subjects. While STEM has been examined here in terms of the three distinct components, the interrelationships of these elements must also be addressed in order overcome the barriers that still exist to implementation of STEM education. For example, surveys conducted by Coppola, et al., [35] showed that the primary obstacles to STEM teaching and learning were lack of time, support, and need for professional development for teachers, and the lack of appropriate curriculum materials and resources. A study by Guzey and Moore [36] also focused on the lack of quality curriculum materials that not only enable students to make connections among the STEM disciplines, but also support the development of knowledge and skills within and across the STEM disciplines. Their solution was to provide a professional development program for teachers on STEM integration that included the design and implementation of curriculum units by the teachers with support by the authors.

In addition, the actual definition of STEM education can still have variations in its interpretation and continues to be a subject of debate, both in content and approach. For instance, going beyond most accepted definitions of STEM education, as discussed in this paper, there also exists a definition of STEM literacy as a vibrant process that could change over time, not a paradigm, and the need to use STEM literacy for continued learning [37]. A study by Nathan, et al., [38] described the fundamental complexity of problem-based learning in terms of instruction and curriculum. They reported that connecting conceptual relationships through mathematical notation and models, scientific laws, technological objects and engineering design promotes student understanding of the links between concepts of different STEM areas and to concepts studied in earlier lessons. Further, these connections can promote STEM integration and student learning when they are addressed through classroom instruction and curriculum design.

These studies point to the significance of the NGSS [5] as the vehicle to implementation of STEM in classroom instruction and learning. It is recognized that the NGSS is not a curriculum, but that it can and does provide guidance for effective STEM education across grade levels. The strength of the NGSS lies in its structure, which includes:

- Performance Expectations:
  - What students should be able to do that demonstrates their acquisition of specified skills and/or knowledge.
- "Foundation'—incorporates:
  - A science or engineering practice.
  - A core disciplinary idea.
  - A crosscutting concept.
- Connections:
  - To other ideas within the S & E disciplines.
    - Within a grade level.
    - Across grade levels.
  - With Common Core State Standards in Math & E/LA.

A cross-cutting concept [39] is particularly important as it can provide the connections between conceptual relationships through science, technology, engineering, and mathematics. Such cross-cutting concepts as models, systems, and patterns are very important to the different subjects, and provide valuable connections between the subjects.

Defining the system and specifying its boundaries can provide a model of that system and the tools for understanding and testing concepts or designs that are applicable throughout science and engineering. Models are valuable in predicting a system's behaviors or to diagnose for problems or failures in the functioning of the system. Students can use their mathematical knowledge to model and solve real-life applied problems involving data, patterns, design, and science concepts. The connections provided by these crosscutting concepts allow students to solve problems from a wide variety of advanced applications in nonmathematical situations, using a variety of representations, tools, and technology to link modeling techniques and purely mathematical concepts to solve applied problems.

4. Conclusions

STEM remains for many a source of ambiguity. For some, STEM still lacks a clear definition. The four disciplines are not meant to be studied as if each one (Science, Technology, Engineering, and Mathematics) exist in isolation from each other where students are achieving skills and knowledge independently in each subject area. STEM is meant to be an interdisciplinary area of study that integrates the four disciplines while providing students experiences in problem-solving, analytical, and communication skills. STEM implementation can be described in terms of a coherent process of the three components: Instruction, Curriculum, and Assessment, where the students are being given the opportunity to learn and the extent of student learning is measureable.

Many engineering/technology teachers have attempted to integrate more math and science into their courses, and where successful have implemented a STEM approach. Others have tried to highlight the ways in which science and mathematics concepts were included in the instruction. Such an approach does not usually involve the utilization of these concepts in solving engineering problems and thus there is no integration of the different subjects.

Implementation issues are discussed in terms of the three components of instruction, curriculum, and assessment. It is widely accepted that science and math teachers have little or no experience with engineering principles and practices, and therefore need effective professional development to implement STEM in their classrooms. Effective professional development approaches are described. Quality curriculum materials are needed for implementation. While the Next Generation Science Standards (NGSS) can serve as a vehicle for implementation, NGSS is not a curriculum. NGSS provides performance expectations that can be used to measure student achievement. Curriculum provides the connection between instruction and learning. Three approaches to implementing STEM curriculums are described: explicit instruction of relevant math and science concepts in the pre-engineering/technology classroom, integration of engineering concepts and practices into science and mathematics courses, and aligning CTE programs with STEM. Assessment of student learning should be an embedded the lesson plans which should include descriptions of student work products that allow determination of students acquisition of specified skills and knowledge and aligned with the performance expectations of the standards.

While implementation of STEM as an interdisciplinary area of study, recognition of the complexity and varying perspectives of STEM education must still be considered in terms of the content of the professional development programs and curriculum modifications. Although treated as separate sections in this paper, they cannot be treated as separate areas in any professional development program. And coverage of STEM must be embedded in the utilization of the NGSS, its connections to the Common Core Standards, and to the connections between disciplines provided by such tools as crosscutting concepts.

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