Science, Technology, Engineering, and Mathematics (STEM) Education
What Form? What Function?

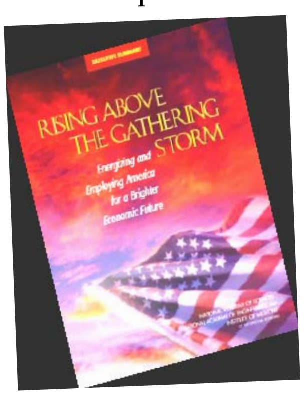
What is STEM Education?

Science, technology, engineering and mathematics (STEM) education often has been called a meta-discipline, the "creation of a discipline based on the integration of other disciplinary knowledge into a new 'whole'. This interdisciplinary bridging among discrete disciplines is now treated as an entity, known as STEM (Morrison, 2006). " STEM education offers students one of the best opportunities to make sense of the world holistically, rather than in bits and pieces. STEM education removes the traditional barriers erected between the four disciplines, by integrating them into one cohesive teaching and learning paradigm. Morrison and others have referred to STEM as being an interdisciplinary approach. "STEM education is an interdisciplinary approach to learning where rigorous academic concepts are coupled with real-world lessons as students apply science, technology, engineering, and mathematics in contexts that make connections between school, community, work, and the global enterprise enabling the development of STEM literacy and with it the ability to compete in the new economy (Tsupros, 2009)."

This author contends STEM education is greater than any interdisciplinary paradigm. It is actually trans-disciplinary in that it offers a multi-faceted whole with greater complexities and new spheres of understanding that ensure the integration of disciplines. This concept is further reinforced by Kaufmann (2003) and by the fact that new innovations and inventions today tend to be made at the boundaries of these four disciplines, where they naturally overlap. Biochemistry, biomechanics, biophysics, biotechnology, and bioengineering are representative of the overlapping of the discipline we know as biology.

Why STEM Education Now?

With the publication of *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Future* (National Academies Press, 2005) our nation became more aware and began to address the mounting concern about having enough scientists, engineers, and mathematicians to keep the United Sates in the forefront of research, innovation, and technology. "In a world where advanced knowledge is widespread and low-cost labor is readily available, the advantages of the United States in the marketplace and in science and technology have begun to erode. A comprehensive and coordinated federal effort is urgently needed to bolster competitiveness and pre-eminence of the United States in these areas." This congressionally requested report made four recommendations along with actions that federal policy-makers should take to create high-quality jobs and focus new science and technology efforts on meeting our nation's current and pressing needs, especially in the area of clean, affordable energy. The four recommendations were: 1) increase America's talent pool by vastly improving K-12 mathematics and science education;



2) sustain and strengthen our nation's commitment to long-term basic research; 3) develop, recruit, and retain top students, scientists, and engineers from both the United States and abroad; and 4) ensure that the United States is the premier place in the world for innovation. In April 2009, the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, revisited their 2005 study by convening a national convocation on *Rising Above the Gathering Storm Two Years Later: Accelerating Progress toward a Brighter Economic Future.* During the event the committee took stock of what has occurred since 2005. Some major accomplishments have transpired, including the passage of the bipartisan America COMPETES Act (August, 2008). In addition, actions by several states and by the private sector have added to the momentum of the STEM education initiative.

Missing the Mark

What changes have actually occurred in the K-12 classrooms in this country since 2005? Have we seen far reaching innovations in curriculum and program design and in the structure of schools that would add to this STEM movement? Unfortunately, the answer is a resounding "No."

American high schools still remain highly departmentalized, stratified, and continue to teach subjects in isolation, with little to no attempts to draw connections among the STEM disciplines. Having worked in and visited numerous school districts within the past three years the author has observed many well-meaning curriculum developers and classroom teachers who indicate they are implementing a STEM program. This implementation usually resembles actions in which science, mathematics, and technology teachers plan and teach cooperatively. This may be a start; however, it misses the mark! If this is the extent of STEM program and curriculum development, then there really is no program or curriculum, as the program and curriculum will disappear (if there ever was one) when the teachers change teaching assignments, transfer, retire, or leave the profession. This represents personalization and not institutionalization. Many educators have not yet come to the realization that STEM education is more than simply a new name for the traditional approach to teaching science and mathematics. Nor do they understand that it is more than just the grafting of "technology" and "engineering" layers onto standard science and mathematics curricula. As a result, there is little to no thoughtfully planned and implemented STEM curriculum in secondary schools. While many would argue this is a start to realizing STEM education within secondary schools, it is a far cry from actually planning, writing, and implementing an innovative, trans-disciplinary STEM program.

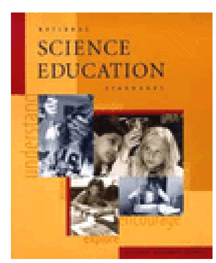
What is happening at the elementary and middle school levels? Teachers at these levels are ill prepared to teach the STEM disciplines of science and mathematics, as revealed by the low numbers of highly qualified teachers. For now there are no national STEM standards or STEM teacher certification. If this is the case, are we really serious about STEM education and do we have it as a national priority? The vision of STEM education, as advocated by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, is far from becoming a reality in the United States and will not be realized until the goals of STEM education are better delineated, the meta-discipline of STEM education is better defined, innovative STEM education programs and curricula are developed, and teachers are professionally educated to deliver new STEM programs and curricula. In other words, the form, which includes program and curriculum design, and function, which are the desired results of STEM education are still largely undeveloped.

What Should be the Function of a K-12 STEM Education?

One of the recommendations of the committee for *Rising Above the Gathering Storm* is the creation of K–12 curriculum materials modeled on a world-class standard. This would help to foster high-quality teaching with world-class curricula, standards, and assessments of student learning. To accomplish this, the report goes on to state, “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. The model for this action is the *Project Lead the Way* pre-engineering courseware.” The work of the committee is most laudable; however, it still falls far short of providing an operational definition of world-class standards and concomitant curriculum.

Part of the underlying problem is the lack of a clear definition of what the implementation of STEM education should accomplish. Albeit, there have been attempts to define the desired results (function) of STEM education, including the four recommendations outlined by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine; but still little to no consensus exists. These four recommendations begin to define the function of STEM education; they do little to describe what it should look like (form) in the classroom. Morrison (2006) outlined several functions of a STEM education. She suggested that students should be:

- **Problem-solvers** – able to define questions and problems, design investigations to gather data, collect and organize data, draw conclusions, and then apply understandings to new and novel situations.
- **Innovators –** creatively use science, mathematics, and technology concepts and principles by applying them to the engineering design process.
- **Inventors** – recognize the needs of the world and creatively design, test, redesign, and then implement solutions (engineering process).
- **Self-reliant –** able to use initiative and self-motivation to set agendas, develop and gain self-confidence, and work within time specified time frames.
- **Logical thinkers** – able to apply rational and logical thought processes of science, mathematics, and engineering design to innovation and invention.
- **Technologically literate** - understand and explain the nature of technology, develop the skills needed, and apply technology appropriately.



What standards would be used to develop such a trans-disciplinary STEM curriculum? What world-class standards as called for in *Rising Above the Gathering Storm* should be used? Fortunately, such standards already exist in the form of The National Science Education Standards (NRC, 1996); the National Council of Teachers of Mathematics Standards (NCTM 1989 and 2000); the National Education Technology Standards for Students (ISTE, 1998, 2007); and the Standards for Technological Literacy (ITEA, 2007). These standards represent a national consensus of the scientific, mathematical, and engineering communities of what constitutes quality education and the educational systems needed to support that education. They were reviewed by thousands of scientists, mathematicians, and engineers, along with dozens of professional societies before being released. They are as world-class as any standards. Many of the criticisms leveled at these standards are in their interpretation by the various state departments of education and not on their desired results or intent. Consequently, an exemplary, trans-disciplinary STEM curriculum should be driven by these four sets of standards.

What are the Barriers to STEM Education in the United Sates?

There have been a number of barriers to realizing STEM education in public schools of this country. Helping to create these barriers have been many misconceptions, including:

- STEM education is just another “fad” in education and will soon go away.
- Colleges will not accept credits for high school courses called STEM.
- Technology means additional computers and hardware for schools and students.
- Technology means the ability to use and apply word processing, spreadsheets, and PowerPoint.
- All inquiry is open-ended.
- Hands-on learning and inquiry are the same thing.
- STEM education does not include laboratory work or the scientific method.
- All STEM educated students will be forced to choose technical fields because they do not have a liberal arts foundation.
- Mathematics education is not part of science education.
- STEM education addresses only workforce issues.
- Technology education and engineering are disparate and troublesome.
- Technology Education teachers cannot teach science or mathematics.
- Engineers cannot teach science and math.
- Technology and engineering are additional courses to be taught and layered as are science and mathematics courses.
- STEM education consists only of the two bookends – science and mathematics.

Until these misconceptions are addressed and corrected, the form and function of STEM education in the United States will remain ill-defined and amorphous.

What About the “T and E” in STEM?

One of the misconceptions identified as a barrier to STEM education was “STEM education consists only of the two bookends – science and mathematics.” This is true today in most K-12 schools in our nation and is largely due to the lack of understanding of how “T and E” fit into the trans-disciplinary nature of STEM education.

The engineering component of STEM education puts emphasis on the process and design of solutions, instead of the solutions themselves. This approach allows students to explore mathematics and science in a more personalized context, while helping them to develop the critical thinking skills that can be applied to all facets of their work and academic lives. Engineering is the method that students utilize for discovery, exploration, and problem-solving. According to the American Society of Engineering Education (ASEE), “Engineering design, by its very nature, is a pedagogical strategy that promotes learning across disciplines. A K-12 engineering curricula introduces young students to relevant and fulfilling science, technology, engineering, and mathematics (STEM) content in an integrated fashion through exploration of the built world around them.”

The technology component allows for a deeper understanding of the three other components of STEM education. It allows students to apply what they have learned, utilizing computers with specialized and professional applications like CAD, CAM, and computer simulations and animations. These and other applications of technology allow students to explore STEM subjects in greater detail and in practical application.

What Should be the Form of STEM Education Curricula?

What about the world-class STEM curriculum and materials called for in *Rising Above the Gathering Storm?* Several curriculum products have recently emerged from National Science Foundation funded projects and have application to some of the components of STEM education. Most notable are: *Engineering by Design*, a K-12 engineering curriculum from the Center for the Advancement of Teaching Technology and Science (CATTS), *Engineering is Elementary (EiE)* from the National Center for Technological Literacy (NCTL), and the *Invention, Innovation, and Inquiry* materials from the International Technology Education Association (ITEA). All are widely recognized curricula exemplars in engineering; but do they fit the trans-disciplinary definition of STEM curriculum? There is little doubt these curricula are exemplary in promoting the “T and E” in STEM, but do they promote the “S and M” as well? To answer this, consider two examples. Quoting from the introduction to the EiE materials, “These materials (EiE) are not an independent curriculum. Rather, it (EiE) is integrated with science; the lessons assume that the students are studying or have already studied the science concepts that are utilized in the engineering lessons. The EiE curriculum does not explicitly teach science topics; although science content may be referred to or reviewed *(Engineering is Elementary*, 2005).” No reference is made to mathematics in the EiE curriculum. In the *Invention, Innovation, and Inquiry* curricula, reference is made to integrating the engineering and technology content with appropriate science and mathematics content; however, no science or mathematics content is listed or specified. None of these curricula fit our definition of trans-disciplinary. What is needed is a curriculum that teaches not only the science and mathematics contained within national and state standards, but also the technology and engineering as detailed in ISTE and ITEA standards. This would make the curriculum truly trans-disciplinary.

What then should be the form of a STEM curriculum that is driven by NRC, NCTM, ISTE, and ITEA standards? What philosophical and theoretical elements should be used to guide the design and development of such a curriculum? What research and field testing support these elements? The following elements should be integral to the design of any STEM curriculum.

- Standards driven - All four sets of national standards cited above (NRC, 1996; NCTM, 2000; ISTE, 2007; and ITEA, 2007) are used to backward map the curriculum. The standards represent the Desired Results Stage One of the curriculum design process known as *Understanding by Design* (Wiggins and McTighe, 1998).”By building on the best of current practice, standards aim to take us beyond the constraints of present structures of schooling toward a shared vision of excellence (NRC, 1996).”

- *Understanding by Design* (UbD) – UbD is one of the most widely used and research-supported curriculum design paradigms in use today. Many countries, state departments of education, schools of education at the college and university level, informal education entities, and commercial publishers model their curriculum on the UbD template. The three stages of curriculum development advocated by UbD (i.e., Desired Results, Assessment Evidence, and Learning Plan) represent a rational and logical approach to using standards (Desired Results) to backward map the assessment evidence and learning plan.

  “Since Wiggins and McTighe first published *Understanding by Design* in 1998 their work has steadily increased in popularity as it fills in many of the blanks for educators striving to meet new state and national standards while maintaining their belief in constructivist teaching pedagogy. While UbD is not exclusively a model for constructivists, it lends itself to sound instructional design principles regardless of orientation to teaching and learning. Today the principles of backward design espoused in this landmark work are being implemented in schools around the world as dialogue continues on educational reform in the twenty-first century (McKenzie, 2002).”

- Inquiry-based teaching and learning – All four sets of national standards cited above (NRC, 1996; NCTM, 2000; ISTE, 2007; and ITEA, 2007) advocate the use of inquiry to reform education. Activities within a STEM education curriculum should scaffold from confirmatory, to structured, to guided, and to open inquiry (CurrTech Integrations, 2008).

  It has been hypothesized that students who learn by inquiry-based teaching strategies will show a greater understanding of content and concept acquisition than students learning through expository learning. Examples of an inquiry approach have been documented in studies by Odom (1996), Rutherford (1998) and Brown (1997). Each research study sets out to compare science scores from students involved in expository versus innovative teaching practices. Their research results describe increase science comprehension and achievement and more positive attitudes towards science.

- Problem-Based Learning - (PBL) is a student-centered instructional strategy in which students collaboratively answer questions and solve problems and then reflect on their experiences (inquiry). It was pioneered and used extensively at McMaster University, Ontario, Canada. Characteristics of PBL are:

- Learning is driven by challenging, open-ended problems.
- Students work in small collaborative groups.
- Teachers take on the role as "facilitators" of learning.

Research on project-based learning has shown results similar to that of inquiry-based teaching and learning. Diffily (2001) describes how both teachers and students benefit from using project-based learning.

- Performance-based teaching and learning – Much evidence has been gathered about how performance-based teaching, learning, and assessing provides the means for improving student achievement (Borko et al. 1993, Falk and Darling-Hammond 1993, Gearhart et al. 1993, Kentucky Institute for Education Research 1995, Koretz et al. 1993, and Smith et al. 1994). For example, research indicates that teachers in Vermont, Maryland, and Kentucky are asking their students to write more and to do more work together in groups. Such research is providing the empirical information needed to examine the tenets underlying assessment reform efforts.

- 5E Teaching. Learning, and Assessing Cycle – The 5E cycle (Engagement, Exploration, Explanation, Elaboration, and Evaluation) has been advocated by many curriculum designers and educational researchers as an effective planning and teaching paradigm that leads to improved student performance (Colburn, A., and M.P. Clough. 1997). Since its introduction in the 1980's, the 5E cycle has been extensively researched, with the results showing enhanced mastery of subject matter**,** increased ability in developing scientific reasoning, and positive increases in cultivating interest and attitudes about science (Lawson, 1995).

- Digital curriculum integrated with digital teaching technologies – STEM education affords an opportunity to deliver curricula to students in non-traditional ways. It is time that high quality digital curricula be developed and be made available to classroom teachers and curriculum designers at the local level. Digital curriculum has many advantages over traditional, analog (paper-based) curriculum. It can be web-based, meaning it can be readily accessible from any Internet-connected computer, can be accessible to people with disabilities, can be readily updated by teachers and/or school districts, and is often more current. In addition, digital teaching technologies such as computers, interactive whiteboards, tablets, student response systems, LCD projectors, digital cameras, and digital microscopes can be used to complement the digital curriculum delivery. A STEM education curriculum should be designed to take full advantage of the digital format.

- Formative and summative assessments with both task and non-task specific rubrics – Today's standards are comprehensive in skills and processes, inquiry, and content; are robust and rich; often have multiple "right" answers; and require performances to assess them. Consequently, traditional modes of using selected response assessments alone are not sufficient to gather evidence of student understanding of these standards. As a result, complementary and alternative forms of assessment have emerged. Alternative assessment means any assessment format that is non-traditional, which requires the student to construct, demonstrate, or perform (Doran, et. al., 1998). With these assessments, tools known as rubrics have gained widespread use in K-16 education (Lantz, 2004).

Summary

STEM education will never realize the vision that was expressed in *Rising Above the Gathering Storm* until several specific actions are taken. STEM education is largely still without well defined form and function. This underlying and unifying theme of function and form must be addressed to guide school restructuring, as well as STEM education program and curriculum development. Most implementations of STEM education in K-12 schools have centered on the "S and M" of STEM, and not the "S, T, E, and M". Engineering and technology have not received equal attention in this version of STEM education. To implement STEM education and problem-based learning (PBL), engineering as a discipline must be be emphasized, as engineering is one discipline centered on solving problems. Consequently, STEM education curricula should be driven by engaging engineering problems, projects, and challenges, which are embedded within and as culminating activities in the instructional materials. This PBL design allows for the teaching of the underlying and supporting science, mathematics, and technology skills, processes, and concepts, and in turn makes the curriculum trans-disciplinary.

STEM education curricula should be planned and constructed around several non-negotiable design elements. A STEM education curriculum should minimally:

- be trans-disciplinary in its overall approach;
- be driven by standards that complement the trans-disciplinary philosophy;
- use the backward mapping techniques advocated in *Understanding by Design;*
- use both problem-based and performance-based teaching and learning;
- use the 5E teaching and learning cycle to plan units and activities within the curriculum;
- be digital in format and coupled with digital teaching technologies such as whiteboards, tablets, student response systems, etc.; and
- use both formative and summative assessments with task and non-task specific rubrics.

These design elements can be blended and molded in the hands of skilled curriculum designers and classroom teachers into world-class curricula necessary to implement and teach STEM education PreK-12. If a STEM education curriculum is built around these elements it will, by its very nature, be student-centered and teacher-friendly, and will serve as a design template for any school district for the development of new and comparable instructional materials. Curriculum design elements, as enumerated above, already have been applied to the development of STEM education products by the author and CurrTech Integrations of Baltimore, Maryland.

About the Author

Hays Blaine (HB) Lantz, Jr., Ed.D. is currently Vice President of Curriculum Development for CurrTech Integrations (currtechintegrations.com) of Baltimore, Maryland. He has been an Assistant Superintendent for STEM Education in a large metropolitan school district in Maryland; Director of Science K-12 for two large metropolitan school districts; Principal Investigator on several National Science Foundation Projects; Director of the Howard B. Owens Science Center in Prince George's County, Maryland; a high school administrator; a Title III-IVC Project Director; a high school biology and chemistry teacher; and a national consultant on science and STEM education for many school districts and publishers. He has either taught or supervised all grades PreK-16.

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