21st Century STEM Education: A Tactical Model for Long-Range Success

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Abstract

The manuscript at hand presents an overview of a k-16 tactical model for developing STEM content and STEM education in the 21st century. The premise of the article is that well-conceived STEM education initiated at the secondary level, using practical and traditional academic facts and procedures, can manifest itself in engineering and technology related products, and also visually connect the STEM areas to help create new information. The careful preparation of STEM educators is also considered as a way to help secondary students develop the ability to specialize in STEM content at the collegiate level. Finally, the manuscript suggests that the STEM acronym provides a cyclic model for developing a deep, adaptable, and strategic method of learning STEM content.

Keywords: STEM, STEM Education, Engineering Heuristics, Scientific Method

Introduction

When educational reform issues are mentioned prominently in high level political speeches, it is likely to be followed by passionate rhetoric and debate from many perspectives, some informed and others not. Nowhere is this truer than in the contemporary national debates raging over STEM education. Science, Technology, Engineering, and Mathematics (STEM) education is becoming an ever more popular battleground for politicians and educators due to the relatively and historically low math and science performance of U.S. students in international comparisons (NAEP 1990-2011). American students lack the ability to compete with their contemporaries from other industrialized nations on tests of technical subjects, and the problem is not a new one (USDE, 2008). Reports from decades ago such as A Nation at Risk (NCEE, 1983) illustrate a set of problems with a lingering history and which show few improvements as we work our way into the new millennium.

Although U.S. students have gained some ground over the past few years, indicators on standardized measures such as the National Assessment of Educational Progress (NAEP, 1990-2011) are still not encouraging. Current educational and political climates appear to promise more of the same attention well into the foreseeable future. STEM was even mentioned prominently in President Obama's 2011 State of the Union address, which indicates a general need to address a growing educational crisis, but to what eventuality? To move toward a viable solution, there needs to be greater consensus in defining STEM education within a specified set of goals, greater commitment to implementing STEM instructional programs with *legs,* and a greater understanding of how STEM assessment works (Becker & Kyungsuk, 2011; Rogers, 2003). The manuscript at hand will provide an overview of a tactical model of STEM education underscored by the need for longstanding definitions of science as a *method* of inquiry and *engineering* as a constructive *heuristic*.

A Brief History of STEM

The political tone of recent months has captured significant public attention with the promise of copious amounts of federally allocated dollars to fund new STEM Initiatives such as *Educate to Innovate (2011).* The problem with all of this political posturing and fiscal maneuvering, however is that politicians, educational reformists, and even educators in STEM disciplines have markedly under-conceptualized what STEM education is and how it should be facilitated in schools and universities (Narum, 2008). Education reformists and special interest groups appear to be positioning themselves to be recognized as *STEM experts* in order to secure federal dollars, some even going so far as to claim credit for contributing to the STEM acronym and coining new acronyms such as STEAM, incorporating the arts for the sake of creativity, and STREAM, further incorporating aspects of technical reading (Piro, 2010).

Although the idea of incorporating other important skills into STEM has merit, it really does not address the underlying problems that students have in learning even basic mathematics and science concepts. With all the political and social attention, the issue and focus of STEM has become somewhat clouded; so to help provide clarity, a brief history of the evolution of integrated technical topics and STEM is perhaps appropriate, especially given the nature of the challenges in how we view STEM disciplines and STEM related instruction.

First of all, STEM is not a new concept, despite the forceful rhetoric of those claiming otherwise. The practice of integrating content subjects such as math and science (in order to help provide useful contexts for what is being learned) is not a new idea either. In fact, STEM is not even a new acronym. The idea of content integration was originally explored more than a century ago by the Committee of Ten at Harvard (Eliot, et. al., 1892), as a way to standardize the agrarian school system of the late 1800's. The committee described the facets of a good industrial school system as a set of generalized skills that would promote excellence and a more comprehensive knowledge base for students. In fact, the spirit of integrated instruction in STEM was actually honored in education more in the late 19th century than it is today, as the nation's economic focus moved toward industrialization. In the early 1990's, the National Science Foundation formally coined the STEM acronym we use today to refer to the *individual* content disciplines of Science, Technology, Engineering, and Mathematics, but without the intent to formally integrate the subjects in schools.

Today, STEM education continues to be defined differently by various groups and individuals, with many definitions evolving into a series of one-size-fits-all perceptions. Definitions exist that span a full spectrum of philosophies ranging from STEM simply consisting of additional course offerings of the traditional topics in mathematics and science to STEM being conceived as a non-exclusive meta-discipline; in essence, as a way to provide meaning for each individual subject by contextualizing it within the others. Yet, a single operational definition may actually be inappropriate for achieving the long-range goals our country is trying to achieve. For k-16 long-range success, broad tactical definitions of STEM and STEM education may be more appropriate. Regardless of the definitions of any given group however, logic alone suggests that simply giving traditional pedagogy and traditional curriculum a new name will only continue to produce disappointing results for American students. If STEM education programs are to be successful, educators need to develop a long-range tactical understanding of STEM content and STEM education regardless of their own localized definition.

Content in STEM Education versus Education in STEM Content

As the education profession develops programs to address the evolving STEM teaching and learning needs, a central factor that must be understood is that STEM *content* and STEM *education* are not the same (Sanders, 2009). The perspective that assumes an innate uniformity in all facets of STEM is partly what causes disagreements in how educators should be trained as compared to mathematicians, scientists, and engineers. STEM is going to look different at different levels, and it should. STEM instruction and outcomes are going to look different at the secondary level than they do at the collegiate level, and not just in the expectations and depth of knowledge (Apegoe, 2009). STEM education for teacher preparation programs is going to look different than other college level STEM degrees because it needs to. Preparing teachers in a single STEM content area, as is typically done with mathematics or science teaching certifications, and then requiring them to effectively integrate content and facilitate learning in subjects they do not fully comprehend is an unreasonable expectation. Further, expertise in one STEM discipline does not automatically translate to expertise in another discipline even if the process of scientific inquiry is well understood by the learner (Elliott et. al. 2001; Froyd & Ohland, 2005).

The specialized training that teachers receive in a given content discipline is important to be sure, but teachers need better *integrated* content models from their preparation programs. In short, a degree in a STEM discipline would have the option to be highly specialized while a STEM *education* degree will require a somewhat broader general understanding of the interrelatedness of STEM topics. Secondary level teachers of STEM disciplines must master a broad knowledge base of STEM content and must witness advanced integrated pedagogical models to be able to develop practical conceptual lessons for their students (Haynes & Santos, 2007; Cantrell, Pakca, & Ahmad, 2006). Math teachers need to understand how the specific principles they teach in their math classes have relevance, and are even necessary, to other technical aspects of scientific testing and engineering heuristics. Science teachers need to be able to illustrate advanced algebraic and geometric models of things like molecules, and demonstrate how those molecules can be represented by equations and graphs; and so on.

The specialization realized within STEM education degrees at the collegiate level is in fact a specialized knowledge base in content integrated pedagogies. It is also important to note at this point that a STEM content degree should provide the option to specialize but not the necessarily to obligation to do so. The option to specialize simply comes from the ability to apply the processes of scientific investigation to a broad range of fields, which is the reality for most college graduates entering the workforce. It makes sense that groups with different goals will have different ideas about how to achieve those goals, and so it follows that educators define STEM based on what they believe are important goals. Within this context, we also need to understand that no given definition of STEM is necessarily right or wrong, but rather is a way to outline how we reach our goals. We must be able to define success locally, but we must also be able to define our place in a successful system.

Defining our place in a successful system requires that we understand different perspectives of STEM *success*. This means better understanding the nature of the individual disciplines and also the nature of how they are best taught and learned at elementary, middle, secondary, and collegiate levels. For example, to suggest that our secondary students need to do better in science is an obvious and fairly pointless observation, partly because the statement illustrates that we have under-conceptualized what *better at science* really means when we make such a suggestion. Science is a *way of knowing* and *verifying* not just an organization of collected facts (APS, 2011), so do we mean that the students should become more efficient in the process of acquiring, testing, and verifying new information through a method of scientific inquiry, or that they need to be more attentive to internalizing a large database of scientific facts? A similar question is appropriate for engineering. Engineering is a heuristic, or way of solving a problem, not just a set of principles, so do we focus on the effective implementation of a heuristic or the mastery of specific knowledge (Childress,1996)? The educational community (admittedly with external pressures) typically defaults to the latter in each case because it is more convenient to measure how well students recall facts than to measure a broad integrated understanding of *methods*, but perhaps we need to look beyond the *who*, *what*, *when*, and *where*, that make up our standardized tests and create a greater commitment to asking *why* and *how* when it comes to STEM content.

To better illustrate the need for asking *why* and *how*, consider further the task of "doing better at science." There are many different kinds of science content, and within each science, there are many different sub-sciences. For example, the science of physics includes mechanical physics, optics, thermodynamics, quantum mechanics, waves and vibration, electromagnetism, and relativity. Each of these contains a foundation of facts and sophisticated concepts so vast that most Ph.D.s need to refer to written sources when doing their research. In similar fashion, math should perhaps more appropriately be referred to as maths because there are many branches of mathematics. In classical mathematics curriculums, there exists arithmetic, algebra, geometry, trigonometry, probability and statistics, calculus, abstract math, analysis, combinatorics, topology, etc. There are many different types of each of these as well. For example, in the general field of geometry, there is Euclidean, analytic, projective, differential, hyperbolic, and number of non-Euclidean axiomatic systems. Again, if we intend for students to be involved in engineering, do we mean for them to understand how to engage an engineering heuristic when solving a problem or for them to know specified engineering content within the fields of mechanical, civil, chemical, electrical, or computer engineering? And yet with all of these categories and sub-categories, the STEM acronym itself presumes a discoverable connection between the disciplines. Investigating *how* and *why* provides powerful motivations and insights to instruction at all levels particularly since efforts to master facts only lead to the realization that it cannot be done to completion (Froyd & Ohland, 2005).

None of the previous questions are meant to suggest that a deep understanding of one particular discipline is not important. In fact, the opposite is true. Some degree of specialization is necessary for nearly every learner at some point so that highly specialized problems can be solved. Enormous amounts of knowledge have been painstakingly accumulated over time by experts who specialize in a given area, often with very narrow parameters, and these specialized investigations have resulted the most important and useful discoveries in the modern world. It is perhaps even fair to argue that no historically significant scientific discovery in the modern age has been made by a scientist who remained a generalist. Certainly there is a case to be made for obtaining specialized knowledge, which naturally begs the question, how do we best prepare students to be capable of doing so? Again, STEM is going to look different at different levels, and STEM education needs to be considered very carefully as a somewhat different entity. The point to all of this rhetoric is that secondary level students need to develop scientific inquiry methods and refine effective heuristics for *knowing, testing,* and *verifying* information in order to have the tools to understand how information is interactive, interdependent, and adaptable.

This is certainly important at the collegiate level as well. Specialization in a content discipline comes after we understand the contributions of other ways of visualizing or extending ideas. This way of looking at STEM not only helps define the scope of STEM at each educational level, but also helps to define the most effective methods of instruction and the intellectual performances that are reasonable at each level.

A Tactical Model of STEM Integration

Most educators see a natural overlap in at least some of the primary components of STEM. Graphing calculator technology has been used in math for several decades now, computer simulations are routinely used to demonstrate scientific concepts, and other more common technologies such as those found in Wood Shop are used every day when building and fixing things. There have also been a number of influential education programs that have formally stressed the integration of STEM disciplines such as Activities Integrating Math and Science (AIMS). But the observance of STEM content integration in lesson design provides much more than an occasional and coincidental overlap of math and science topics. It provides a cyclic model for developing a deep, adaptable, and strategic method of *learning* STEM content. The acronym STEM is also more than a designation of four related content disciplines. It actually represents both a hierarchy and a cycle in building a conceptual understanding of how the STEM subjects are interactive and adaptable. Well-conceived at the secondary level, practical academic facts and procedures can manifest themselves in engineering and technology related products, and also visually connect the STEM areas to help create new information. Ultimately, STEM conceptualized and used as a broad-field curriculum design at the secondary level should involve a cycle that values 21st century skills in a way that the disciplines taught in isolation cannot accomplish.

To help clarify this cycle, consider for a moment the main purpose for the advancement of technology. The root of nearly all technological innovation ultimately distills down to an issue of efficiency. Every technological advancement we enjoy today was developed to make our lives easier or more productive in some manner. At the foundation of this development process is mathematics, where we conjecture about and explore relationships and patterns through formalized semiotics, which is basically the study of *symbols* and *algorithms*. Science then uses the *symbols* and *algorithms* of mathematics to derive the formulas and procedures that allows us to provide *physical verification* of our mathematical conceptions. Engineering builds on the *physical verifications* of science as a heuristic to design and transform intellectual conceptions into *tangible product*. Technology is then developed as a way to model, improve, and legitimize the *tangible products* by addressing *efficiency*. Mathematical explorations are again initiated in evaluating the *efficiency* of the new technology so that it can repeatedly be evaluated, improved, and adapted to new situations. If executed appropriately, the cycle becomes a large scale intellectual improvement process.

Earlier in this manuscript, the suggestion was presented that we be able to define our place in a successful system. If the system under consideration is the mechanism by which we create successful STEM students, then we need to look at the mechanism from both concentrated and broad perspectives. At this point we will turn our focus very briefly to the concept of Micro-Macro Dynamics. Micro-Macro Dynamics is a process by which we look at the interactions of micro behaviors within a system and determine how they affect the macro-behaviors of the system itself (Yamori, 1998). We have assumed that preparing STEM students differently at different levels within the educational process is necessary, or at the very least, appropriate. So if the mechanism under study is how long-range success for individual students in STEM education can be facilitated (micro-behavior) but also how positive economic influences for the country can be initiated (macro-behavior) then we need to consider the advantages of preparing students for innovative specializations including *integration* of general disciplines as a specialization. Universities are best suited to provide specialized expertise in the STEM content areas for a number of reasons including the availability of local expertise, specialized facilities, and access to academic and other physical resources, so it is appropriate to assume that the STEM goals of a university would be focused on specialized research and specialized production. Alternately, the STEM model appropriate for secondary classrooms is more general, where learning to learn and learning how STEM content is interactive, interdependent, and adaptable are all central to success.

The most basic idea drawn from the conception of different STEM preparation at different levels is that integrated STEM education at the secondary level is a micro-behavior. It contributes mostly to the success of the *individual* by preparing them to specialize in a STEM discipline if they so choose.

Individuals with the ability and option to progress in difficult STEM related specializations (because they have been properly prepared to do so at the secondary level) contribute more to the *macro-behavior* of the system because they can make specialized contributions in solving highly specialized problems that benefit the larger system of national economy.

STEM Education Assessment

Assessment is the proverbial lock on the gate of student and school success and unfortunately it can only be opened with a skeleton key that no one seems to be able to find. It is true that assessment remains one of the most debated issues in education and that the issues are difficult. Also, assessment is at the core of implementing successful STEM programs at the secondary level so we need to be especially attentive to it. Despite the inherent complexities in accurately measuring school performance, classroom based STEM assessments could be much more effective if we would allow contemporary content and instruction to drive the assessment process rather than allowing the reverse to be true. It is absolutely confounding that against the recommendations of experts at almost every educational level, the educational machine insists on using instruments and techniques that do not and cannot provide the information needed for making effective instructional decisions in classrooms nor accurate statements about the progress of schools in general. The worst part is that we know this to be true and we have known it for a long time.

If we are committed to integrated STEM curriculum and instruction at the secondary level, the kind of instruction that prepares students to effectively specialize in STEM fields at the collegiate level, then we need to build *appropriate* integrated STEM assessments. And this will not be easy because the education world is addicted to discipline-specific standardized testing. Policy makers continue to present statements about school efficacy based on the snapshot results of instruments that are commonly acknowledged in the profession as invalid and irrelevant. The instruments are not valid because discipline-specific instruments (unique to math, science, etc.) do not allow us to determine the efficacy of curriculum or instruction in integrated STEM. Even well-constructed standardized tests cannot measure integrated STEM content because they simply are not designed to do so. They are irrelevant because they do not measure what most professionals in the educational community really care about. Yet, these assessments continue to drive instruction, and indeed, curriculum because teachers are under tremendous pressure to produce *literate* students as defined by the expectations of the invalid and irrelevant evaluation tools. Ultimately, teachers will structure all learning activities to produce what is assessed.

In short, if we continue to use only discipline-specific standardized tests, integrated STEM will never be honored in schools because schools will not change what is taught until school and student success is evaluated differently. All of the discussions, research findings, special program funding, professional collaboration, and teacher professional development will literally be wasted and produce nothing if the way we measure student and school success does not change. So what do we test? Take a lesson from what people working in STEM fields do and examine how they do it. When engineers design and build things, using applied math and the principles of the sciences, they are learning. When scientists work through repeated failures in the process of successfully discovering the nature of matter or chemical compounds, they are learning. When mathematicians spend countless hours identifying the parallel structures of ideas in complex systems, they are learning. Each of these scenarios results in a group of highly specialized professional *learners* that can tell you exactly what they learned and why. They start with a question. They design and carry out the experiments or developmental scenarios of their question. They test the results and derive conclusions to their question. Why should assessment at the secondary level look so different? Because it is inconvenient? At the core of any successful STEM program should be courses in which students ask questions, design experiments, create products, test results, and evaluate conclusions... not just take tests. However, to suggest that we eliminate tests completely is also unnecessary. What will serve STEM learning in the best possible way is accumulate useful information from valid assessment instruments and techniques, and train teachers to meaningfully adapt instruction to accommodate what the assessment data is suggesting (Ostler, Grandgenett, & Mitchell, 2007).

Conclusion

Of course, STEM education discussions should continue in much greater detail than was overviewed in this manuscript, but with an informed realization that a successful STEM program will have unique parts that are potentially different in both form and function.

The learner is central to success at each level, which means we should demand to service that learner in the best way we can at each level, but this can only happen if we recognize the inherent differences in the goals at each level. Acknowledging that STEM teachers need to be trained in a different way than scientists, mathematicians, and engineers is critical to completing a cohesive k-16 STEM program that contributes to all facets of a responsible 21st century learner and citizen. A final thought to conclude this manuscript will relate to the nature of fundamental skills as they have been traditionally addressed in mathematics and science. STEM, by the very nature of current social demands, puts us on a frontier of new curriculum, new instruction, and new assessment; and yet, there will likely remain a fundamental set of basic skills for each of the traditional disciplines well into the future even if integrated STEM changes rapidly. Because technology alone changes so quickly, the underlying issue of specificity in instructional goals will probably have to change because it will become more difficult to recognize what is and what is not a basic skill. Further, we may not even know what those basic skills should look like a decade from now. STEM programs may even bump up against other programs such as Advanced Placement or International Baccalaureate where content is both well established and traditionally measured, which clearly does not fit an adaptable STEM model. There is a sticky philosophical issue related to how we can honor those differences in perception of STEM success, but an honorable profession will not sacrifice the opportunity for students to earn the choice to pursue a STEM career at advanced levels. How we perceive STEM is not as important as a dedication to the learners we serve and the academic options we create for them. To realize this dedication we must look to the future of STEM both holistically and individually; from a general standpoint and a specialized standpoint; with traditional assessments and non-traditional assessments; and finally, with courage and fortitude.

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