The Nature of Interdisciplinary STEM Education

Michael K. Daugherty and Vinson Carter

Abstract

Interdisciplinary STEM education is the pedagogical approach by which students learn the interconnectedness of the disciplines of science, technology, engineering, and mathematics. Interdisciplinary STEM education also provides a platform to introduce problem-based learning, cooperative learning, expand problem-solving capabilities, and introduce students to the use of engineering design. Several research studies suggest that when students are introduced (early) to the STEM disciplines through integrated and problem-centered learning activities, they are more likely to remain engaged throughout formal education and are more likely to enter one or more of these fields as a career.

Keywords

STEM Education • Integration • Interdisciplinary learning • Problem and project-based learning • Performance-based assessment • Integrated STEM curriculum

Contents

M.K. Daugherty (✉) • V. Carter
Department of Curriculum and Instruction, University of Arkansas, Fayetteville, AR, USA
e-mail: mkd03@uark.edu; vcarter@uark.edu

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Introduction

Early efforts to organize the technology education curriculum resulted in borrowing content from adjoining and related disciplines and integrating that content in a single course of study. For example, early drafting courses borrowed heavily from conceptual information typically delivered in mathematics or geometry courses. The desire for students to learn in an integrated fashion can be found in the United States dating back to the founding of the nation. Indeed, the first State of the Union address offered by President George Washington called upon educational leaders in the young nation to establish schools that focused on the promotion of literature, arts, and sciences (The American Presidency Project 2016).

Perhaps due to the lack of a concrete, defining body of knowledge other than an attempt to mirror the practices of industry, technology education has a long history of drawing content from related disciplines like engineering, science, the arts, mathematics, and others. During the nineteenth and early twentieth Centuries in the US, the field of technology education was referred to as manual training, manual arts, and then industrial arts and the rationale for much of the content of those areas was its necessity for national industrial success. The same is true in many other countries. In the latter half of the twentieth Century the field in the USA transitioned to what is now known as technology and engineering education and the curriculum began to draw heavily from science, technology, engineering, and mathematics (International Technology and Engineering Educators Association (ITEEA) 2007).

Vars (1991), noted that an integrated school curriculum is an attempt to help students make sense out of the multitude of fragmented and departmentalized bits of knowledge offered in most schools. Technology education has the potential to be the discipline that would reduce curricular fragmentation through the integration of content from other disciplines. This integration is a clear departure for some of the more traditional program offerings (Daugherty 2005). This curricular integration could involve multidisciplinary or thematic integration, interdisciplinary teams, and intradisciplinary integration (Drake and Burns 2004). Thematic integration involves faculty selecting a common theme that cuts across several disciplines and then delivering instruction related to that theme in different fields of study. Meanwhile, interdisciplinary teaching involves a team of teachers from different disciplines who are encouraged to correlate at least some of their teaching. In an intradisciplinary curriculum, one teacher may take on the responsibility for instruction in several subjects during an extended period of study within a single subject area (Drake and Burns 2004). Even though most in the field of technology education would refer to the curriculum as interdisciplinary, it is likely better defined as intradisciplinary.

As the world entered the twenty-first Century, it became more technologically complex. At the same time, researchers made new discoveries related to learning, and it became evident that forming connections between the disparate components of the school curriculum was essential (Drake and Burns 2004). The integration of the STEM disciplines was perceived to have the potential to aid students in their ability to transfer learning from one discrete field to another as was necessary to solve the problems at hand (Berry et al. 2004). In an integrated setting, students can solve new problems and often draw conclusions based upon previously learned principles drawn from fields like science, technology, engineering, and mathematics (Roberts 2012). Havice (2009) noted that implementing teaching strategies, such as problem-based learning through a STEM curriculum, may also reinvigorate students' desires to understand the world around them and engage them further in classroom instruction.

Roberts (2012) suggested that integrated STEM programs are based on some common characteristics. First, they are integrated utilizing a curriculum centered on principles from science, technology and engineering, and mathematics, where students learn to apply information to creatively seek solutions to given engineering design problems. Second, integrated STEM education is inquiry-based and centered on solving engaging design problems that require the application of information from science, mathematics, and engineering fields. Distinct from the traditional science or mathematics classrooms, which are typically lecture-based or teacher directed, integrated STEM classrooms in technology education require students to work together to solve problems while utilizing questioning techniques, research, and experimentation (Roberts 2012). Finally, integrated STEM incorporates instruction in the "soft skills" needed for business and industry like collaboration, partner dependence, journaling, and design thinking (Partnership for 21st Century Skills 2003).

Unfortunately, the STEM acronym has also been politicized and is often attached to initiatives that have little to do with integrated, inquiry-based, and problem-centered learning. In some cases, the STEM title is used to attract attention and perhaps funding. Bybee (2010) noted that numerous conflicting definitions of integrated STEM may be damaging the effort put forth in high-quality programs that increase participation in the STEM disciplines and suggested that it is important that the STEM education community resolve the definition of the STEM acronym. While many researchers have suggested that STEM education be implemented using an integrated approach to better serve students (Atkinson and Mayo 2010; Mahoney 2010; Sanders 2009a; Satchwell and Loepp 2002), STEM is often attached to curricula and programs that primarily focus on a single discipline and curriculum projects that are obviously not integrated. Meanwhile, numerous research studies conducted in the technology education field have found that an interdisciplinary or integrated curriculum provides students with a meaningful classroom experiences that augment learning (Bybee et al. 1991; Furner and Kumar 2007; LaPorte and Sanders 1993; Loepp 1999; Sanders 2009; Satchwell and Loepp 2002).

Interdisciplinary STEM

Honey et al.'s (2014) report on STEM Integration in K-12 Education defined STEM integration as "working in the context of complex phenomena or situations on tasks that require students to use knowledge and skills from multiple disciplines" (p. 52). STEM education has received increasing attention over the past decade with calls both for greater emphasis on these fields and for improvements in the quality of instruction. In response, numerous new curriculum projects, instructional materials, and teaching approaches have emerged, however leaders in technology education continue to call for more emphasis on the connections between and among the subjects of STEM (Sanders 2009). Advocates for greater integration of the STEM subjects argue that teaching STEM in a more connected way, especially in the context of real-world problems, can make the STEM subjects more relevant to students (Honey et al. 2014). Solutions to problems in society are rarely solved using the knowledge, tools, and skills from one discipline. Often, the unique content, techniques, and contributions from each of the STEM disciplines is used to tackle even the messiest problems that humans encounter. Ideally, interdisciplinary STEM learning mimics authentic real-world problem solving.

Interdisciplinary educational efforts have long been implemented to mirror this concept in the classroom. However, the structure of public schools systems, especially at the secondary level, may stifle collaboration and integration of subject matter. Mahoney (2010) suggests in his study of students' attitudes toward STEM learning that the development of national content standards which advocate for content integration, call educators to action to provide students with opportunities for interdisciplinary learning to "enhance student learning and STEM preparation" (p. 24). This concept was reconfirmed with the releases of the Common Core State Standards for English Language Arts and Mathematics in 2010 (CCSS 2016) and the Next Generation Science Standards in 2013 (NGSS Lead States 2013), all of which provided specific references for the integration of content and interdisciplinary learning and began to elevate the stature of engineering design as a curricular construct.

Additionally, multiple efforts to integrate disciplinary content outside of the STEM disciplines have been seen in recent years. Daugherty (2013) suggested that the integration of the arts into STEM education may be important for the promotion and development of creativity and innovation. Furthermore, Wilson-Lopez and Gregory (2015) described the symbiotic relationship between engineering and literacy in elementary school, and how the engineering design process can be an important tool for engaging students in reading and writing instruction.

Delivering Interdisciplinary STEM Content Through Engineering Design

The engineering design method of inquiry is regarded by some to be the cornerstone of integrated STEM education (Basham and Marino 2013; Berland 2013; Brophy et al. 2008; Stohlmann et al. 2012) and is a tool for fostering creativity, innovation, and inventiveness among student participants. Engineering design can be regarded as the core problem solving process of technology education and is increasingly known as a foundational methodology for all integrated STEM curricula. According to Standards for Technological Literacy:

> It is as fundamental to technology as inquiry is to science and reading is to language arts. To become literate in the [engineering] design process requires acquiring the cognitive and procedural knowledge needed to create a design, in addition to familiarity with the process by which a design will be carried out to make a product or system. (ITEEA 2000, p. 90)

Individuals working in the STEM fields have a number of well-defined methods they use to arrive at logical solutions to the problems they encounter, all of which share common traits (ITEEA 2000). First, designers and innovators set out to meet certain design criteria or solve a given problem. Second, designers must work under constraints such as money, materials, time, and human resources. Finally, a set of logical procedures or steps are used to work toward a reasonable solution to the given problem (ITEEA 2000; Wells 2016). In STEM education, these procedures or steps may be called the engineering design process, the design loop, or a design method. The engineering design process demands critical thinking, the consideration of core concepts from the STEM disciplines, the application of technical knowledge, and creativity. There are numerous models found in the literature (Wells 2016) that attempt to describe the engineering design process. Some of the most widely accepted models illustrate the engineering design process as a loop, circle, or spiral of procedures that, if loosely followed lead to a successful conclusion (ITEEA 2000). These engineering design model attempts to represent the process as an iterative method that includes processes like: Clearly defining the problem, generating multiple potential ideas/solutions, building models and prototypes and testing them, and communicating the results of the effort.

Engineering design can be reasonably defined as a series of steps that engineering teams use to guide them as they solve problems. Thus, engineering design has become an integral component of pedagogy in integrated STEM education. The engineering design process is cyclical, meaning that engineers or problem solvers repeat a series of steps as many times as needed to reach an acceptable conclusion, making improvements along the way. Although there is no single accepted engineering design process, it typically consists of steps or procedures like: (1) conduct research and gather information, (2) conduct rough ideation, (3) propose multiple potential solutions, (4) create a representative model, (5) create a prototype, (6) test the solution; and, (7) communicate the results. Koen (2003) notes that the engineering design process provides a plausible aid or direction in the solution of a problem, but is often an ill-structured method of ideation.

In the simplest terms, the engineering design process (see Fig. 1 above) can be considered to be an algorithm, or a set of steps to follow in an attempt to solve a given problem. The engineering design process, mathematical equations, and computer programs are types of algorithms. The scientific community uses scientific inquiry in a similar fashion. Meanwhile, all sorts of technicians use analogous techniques or steps to diagnose and repair equipment and machinery. For example, a technician repairing an automobile often seeks to identify the fault in the vehicular system by first making certain that vehicle has fuel, spark, air, and compression – the four ingredients necessary for internal combustion engines to operate (Tracy 2015). In a more formal sense, these learning algorithms are referred to as heuristics that

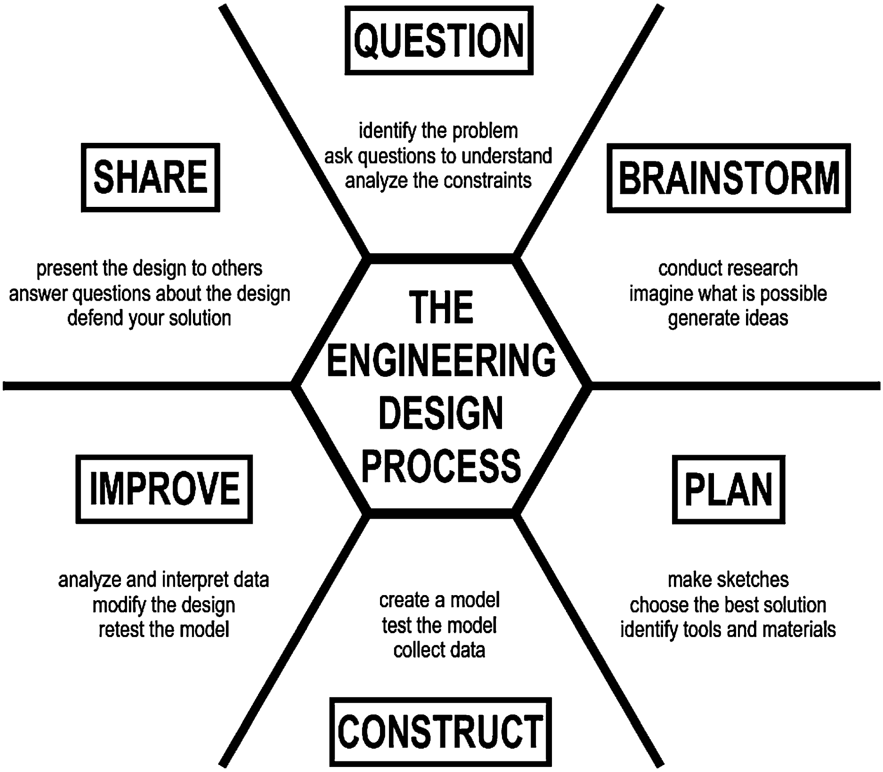

Fig. 1 Example of the engineering design process developed through a collaboration between the University of Arkansas and Springdale Public Schools

support the logical thinking skills and deductive reasoning methods needed to solve STEM problems. A heuristic is a mental shortcut that gives some directions or hints for successfully completing a task or for solving a problem. Engineers and technicians frequently use synonyms for heuristics like intuition, rule of craft, guiding thread, or rule of thumb (Koen 2003). These synonyms vary from country to country. For example, in France the intuition used to solve a technical problem could be referred to as le pif (the nose), in Germany, Faustregel (the fist), in Russia, by the fingers, or in Japan, measuring with the eye (Koen).

While engineering design does not guarantee success, it does provide the problem solver with some practical tools useful for deductive reasoning and for arriving at reasonable solutions to ill-structured problems (Petroski 1992). Pahl and Beitz (2015) noted that engineers use engineering design as a method for applying scientific and engineering knowledge to the solution of technical problems, and then optimize those solutions within the parameters and constraints presented by the original problem. Problems become concrete tasks through the deductive reasoning presented through the implementation of engineering design (Pahl & Beitz). Although solving engineering, or STEM problems calls for sound grounding in mathematics, physics, chemistry, mechanics, and other disciplines; initiative, resolution, tenacity, teamwork, and other psychological skills that are indispensable to the problem solver or designer (Pahl & Beitz). Engineering design emphasizes both the tangible and intangible, as well as the iterative nature of STEM problem solving. This process also provides an invaluable tool for teachers attempting to deliver agreed upon standards for learning.

The Integrated STEM Curriculum

With the popularity and increased emphasis of STEM and project or problem-based learning (PBL) instruction in schools, a plethora of commercially available curricula became available for educators early in the twenty-first Century.

There are a variety of curricular opinions for educators seeking an appropriate STEM curriculum. While off-the-shelf curricula provide educators with readily available materials, these materials sometimes lack the local buy-in that will be critical if lasting change is to be created. Subsequently, many STEM educators and technology education teachers develop their own project-based, engineering design driven, performance-based assessment STEM curriculum. These curricula are based on authentic STEM problems drawn from the local community and connected with the learners. Most STEM educators utilize the backwards curriculum design process popularized by Wiggins and McTighe (2005). This curriculum planning process provides a structure to guide curriculum, assessment, instruction, and to meet learning standards. Backwards curriculum design is focused on teaching and assessing for understanding and learning transfer, and starting the planning process with the desired outcome as a guide (Wiggins and McTighe 2005).

The Role of the STEM Teacher

The role of the STEM teacher is similar to the teacher in any project or problem-based learning (PBL) environment. The characteristics of a PBL classroom include the teacher as a facilitator of learning, the students are responsible for self-directed and regulated learning, and learning is comprised of ill-structured learning challenges (Savery 2006). Savery contends that one of the most difficult challenges for teachers in a PBL learning environment is the transition into the role of a facilitator.

A chief concern in STEM education is the preparation of educators with both content knowledge and the ability to integrate STEM education learning into the K-12 classroom (Stohlmann et al. 2012). Honey, et al. contended that the:

> The expertise of educators, whether in classrooms or in after-/out-of-school settings, is a key factor – some would say the key factor – in determining whether the integration of STEM can be done well. At the most basic level, educator expertise combines knowledge of the subject matter with an understanding of effective approaches for teaching it to students with diverse learning styles. Such approaches include not only teaching strategies but also the

skill with which educators plan lessons and work collaboratively to support student learning (Honey et al. 2014, p. 115).

Stohlmann et al. (2012) identified a model for teaching integrated STEM education. Their model consists of four major components including opportunities for collaboration and professional development, teaching with focus on integrated lesson planning and effective classroom practices, efficacy and a commitment to STEM education, and access to materials and resources needed to implement instruction. The increased emphasis on STEM education and the ambiguity of how it should be taught provide an opportunity for the technology education profession. The technology education profession can stake the claim for teaching engineering at the K–12 level, align with the engineering profession, and reform its instructional practices to reaffirm its place in the core curriculum (Strimel and Grubbs 2016).

The Promise of Early Intervention

A number of research reports indicate that children's ambitions and confidence in science and other STEM areas are largely formed by the time they are 10–14 years old and diverge little after this age (Murphy 2011; Archer et al. 2012, 2013; DeJarnette 2012). Because interest in STEM subjects and STEM careers is largely formed by the time children reach the upper elementary or middle school level, it is vital that children be engaged in rich STEM learning experiences in early elementary grades, long before the point at which they enroll in courses leading to eventual career paths during high school and college. Unfortunately, most STEM initiatives and projects, especially in the USA, are launched at the secondary school level – long after the majority of students have made the decision that they do not like science, or that they are not good at math. Many of these students avoid the STEM disciplines for the rest of their lives and programs designed to engage them are too little, too late (Daugherty et al. 2014).

The combined effects of educational reforms and accountability demands arising from recent technological and economic changes are requiring schools to accomplish something they have never been required to accomplish previously – substantially ensure that all students achieve at a relatively high level academically (Corcoran and Silander 2009). Meeting that challenge has required educational leaders to reexamine the curriculum, the instructional delivery system, and the level at which core subjects are taught. Unfortunately, if STEM was emphasized at all, most schools started STEM instruction at the secondary school level (Means et al. 2008). In 2008, Means, et al. found that there were 315 public schools in the United States that referred to themselves as STEM schools and 86% of those schools served students in grades 9–12 while only 3% served students in grades 1–5. Anthony Murphy, Executive Director of the National Center for Elementary STEM Education, noted that we need to begin STEM education in elementary school and possibly even younger (2011). Murphy goes on to note that very young children are natural scientists, engineers, and problem-solvers. They try to make sense of the world by touching, tasting, building, dismantling, creating, discovering, and exploring. Yet, research documents that by the time students reach 4th grade, 30% have lost interest in science. By 8th grade, almost 50% have lost interest or deemed it irrelevant to their future. This means that millions of students are tuning out or lack the confidence needed to pursue a future in STEM fields.

When Pantoya et al. (2015) asked over 300 3–7 year olds “What do engineers do?” during a research project designed to develop engineering identities, the most common response was: “I don’t know.” The 2nd most common response was: “They drive a train.” These responses reflect a fundamental lack of understanding of engineering. Other research points out that by the 4th grade, students who have limited exposure to early STEM education lack key mathematics and science skills and background knowledge (Successful STEM Education 2013; National Research Council 2011; Honey et al. 2014). As noted above, by the 4th grade there is a decline in STEM interest and this decline has been linked to a lack of consistent focus in science and math content, as well as a lack of instructional methods that shape young children’s curiosity to explore the world around them (Kang and Lundeberg 2010); and a lack of focus on scientific literacy (Gibbons 2003). Pantoya et al. (2015) argue that “early experiences are critical to developing a students’ engineering identity” (p. 61).

After examining a variety of elementary STEM programs across the nation, Dejarnette (2012) noted that students who complete STEM programs in high school have a greater likelihood of continuing in a STEM concentration for college/careers and the same would occur between the elementary school and the middle school if STEM programs were expanded during the early grades. To increase the number of students interested in STEM at the middle school and high school, these concepts should be presented during the elementary grades. In secondary education, effective teachers with content knowledge in STEM play a key role in student achievement. Almost all of these secondary STEM teachers have a degree in one of the STEM disciplines, but elementary teachers are generalists and typically major in education. It should not surprise anyone to learn that elementary teachers are somewhat apprehensive about teaching STEM – in large part because, they were not prepared to teach some of the disciplines represented in STEM effectively. If they lack confidence, they are likely to avoid teaching STEM.

Elementary STEM education that includes vast opportunities for students to engage in project-based learning, the engineering design process, integrated content from adjoining disciplines, and performance-based assessment must become a defining goal of technology education (Daugherty et al. 2014). Such programs will not only inspire heightened levels of curiosity, creativity, and innovation among participating students, but will also ensure that the next generation will have a markedly greater understanding of the core concepts of science, technology, engineering, and mathematics.

Conclusion and Future Directions

STEM education has gained widespread attention from educators, politicians, state and federal agencies, and the media. This attention is often connected to the assumption that children are retreating from the STEM fields, which may lead to decreases in national and international competitiveness. Subsequently, there have been calls for transformation, new standards have been developed, governmental agencies have issued reports, and many leaders have called for an increased treatment of STEM education in schools.

Meanwhile, technology education, with a long history of integrating content from related disciplines, seems an ideal program to cement STEM into the school setting. In 2000, Standards for Technological Literacy was published in the USA and this document made the case that technology education should play a role in students' learning STEM. Moreover, Standards for Technological Literacy, as well as standards from the fields of science and mathematics, called for increased attention to an integrated curriculum and less emphasis of disciplinary fragmentation and departmentalization. As the world entered the twenty-first Century and became more technologically complex, researchers developed evolved theories related to learning, and it became evident that forming connections between the STEM disciplines in school was essential.

Other researchers began to note that in addition to the integration of content from the STEM disciplines, such programs should utilize instructional strategies focused on authentic problem solving and creativity, as well as inquiry-based engineering design problems and performance assessment. These advocates called for STEM education to be delivered in a more connected way, especially in the context of real-world problems, making integrated STEM subjects more relevant to students – fostering creativity, innovation, and inventiveness among student participants.

Other researchers noted that such STEM programs should be launched much earlier in the educational process. A number of research reports indicated that children's ambitions and confidence in STEM was largely cemented by the time they were 10–14 years old and that it was vital that children be engaged in rich STEM learning experiences in early elementary grades, long prior to making eventual career decisions.

The nature of interdisciplinary STEM education is in flux, however opportunities await those educators seeking to develop and implement interdisciplinary educational programs that center upon core content from the STEM disciplines. Particularly those educators who desire to deliver such programs through engaging and authentic, project-based learning mechanisms at an early age.

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