

Technology Education and Designerly Ways of Knowing: The Pedagogical Goal of Design is Understanding

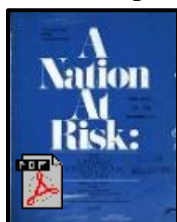
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Abstract

Improving student understanding by connecting content and practices through curricula that integrates science, technology, engineering, and mathematics (STEM) has been a national priority in the United States for well over half a century. This educational reform has resulted in the U.S. now fully embracing technological/engineering design based learning (T/E DBL) strategies as a means of ensuring STEM integration and achievement of student understanding. Student understanding is the principal learning outcome to be attained through T/E DBL where the instructional goal is explicit in “having students design to understand” when working toward the development of a viable technological and/or engineering solution that meets a human need (Wells, 2016, pp. 14-15). Immersing students in T/E DBL experiences develops their habits-of-hand (designerly abilities) that intentionally leads to their developing the habits-of-mind (designerly ways of knowing) requisite of true understanding. As an approach to acquiring knowledge and achieving understanding, designerly ways of knowing (Cross, 1982) is unique to the T/E design based learning approach. This article provides classroom exemplars as a means of demonstrating how T/E DBL uniquely imposes on learners a need-to-know requiring them to draw on multiple STEM subjects as they move between convergent thinking (what they know) and divergent thinking (what they need to know) when working to learn the content knowledge and practices needed in designing technological or engineering solutions.

1. Educational Reform: Impacts on Technology Education

Improving student understanding by connecting content and practices through curricula that integrates science, mathematics, and technology (SMT) has been a national priority in the U.S. for well over half a century. For example, in the early 1980s publications such as *A Nation At Risk*, *Science for All Americans*, and *Benchmarks for Science Literacy* have given rise to a focus on the integration of SMT as an instructional priority (Wells, 2019). Reflected within these publications was the unmistakable intent to envision the teaching of SMT as an integrative endeavor. This intent is clearly articulated by presenting the concept of science as “...the union of science, mathematics, and technology that forms the scientific endeavor...” (AAAS, 1989, p 25) and “...the ideas and practice of science, mathematics, and technology are so closely intertwined that we do not see how



education in any one of them can be undertaken well in isolation from the others” (AAAS, 1993, pp. 321-322). These documents refute the traditional silo approach to teaching SMT content and practices, and contend that integration is best facilitated through a learning approach where design is a central instructional strategy, such as that being practiced in technology education (NRC, 1996, pp. 135-138). In more recent years, the acronym has changed to STEM, indicating engineering, the “E” in STEM, was now being included within this educational priority. As a



result, educational reform in the U.S. today fully embraces design based learning as the prominent pedagogical approach for improving student understanding by explicitly requiring integration of science, technology, engineering, and mathematics (STEM) content and practices using technological/engineering design based learning (T/E DBL) strategies.

Ensuring that integration remains the educational priority requires that practitioners recognize STEM for what it truly is – it is simply the acronym for science, technology, engineering, and mathematics. Specifically, practitioners need to recognize STEM is *NOT* a separate discipline or a meta-discipline, STEM is *NOT* a field of study, STEM is *NOT* a curriculum, and *STEM* is *NOT* a single school subject to be taught. STEM is an acronym and only meant to convey the concept of transdisciplinary integration. It is a concept of integration intent on moving education beyond the traditional siloed, mono-disciplinary approach, to one that embraces experiential learning where students seamlessly integrate disciplines within authentic and relevant technological and engineering design based learning scenarios.

2. Genesis of an Integrative Paradigm

Much of what we might perceive today as being new in education is not – it has only become newly important. A good example of this is our current perception of STEM education – this is not something new, just newly important. And the same can be said for the presumption that acquiring deep understanding of STEM disciplines is best achieved when the mind is informed by engaging the learner in hands-on experiences. Specifically, developing a learner’s habits-of-mind through habits-of-hand is not new – it has simply become newly important. This minds-on, hands-on approach to teaching has long been the pedagogical premise of Technology Education. One where teachers engage learners in their technological world in order for them to understand the nature of the technologies that sustain it. The design approach to teaching and

learning is a naturally integrative pedagogy unique to Technology Education, and one clearly aligned with the educational ideals of the discipline. Within these ideals the role of technology education is to serve as the “great integrator” (Wells, 2012) of content and practices inherent to the designed world.

Emergence of Integrative STEM Education. First publicly coined spring of 2008¹, Integrative STEM Education embodies the signature pedagogy of Technology and Engineering Education (TEE) and provides the premise for teaching the content and practices within that discipline. As with all other disciplines, TEE has a long-established epistemology reflecting the theory of knowledge for the field; its validity, scope, and method. The signature method for implementing TEE is technological/engineering design based learning (T/E DBL), where the educational goal of designing is to have the learner achieve understanding. Achieving this goal requires that educators of technology and engineering focus their instruction not just on engaging the learner in producing an artefact, but more importantly on ensuring the learner gains understanding as a result – students of TEE *design to understand* (D2U).

In 2010 the international association for teachers of technology education formally changed its name to the International Technology and Engineering Educators Association (ITEEA). At the same time the ITEEA began characterizing Technology and Engineering Education as the only discipline whose Standards for Technological Literacy (STL) (ITEA/ITEEA, 2000) were conceived of and intended to teach S.T.E.M. content and practices as an “integrative” endeavor (Wells, 2013, p. 29). The discipline of Technology and Engineering Education (TEE) is represented by the “T” and “E” in STEM education, and the STL are explicit in envisioning technology as a way to “integrate knowledge from many other disciplines – not just mathematics, science, and computer classes, but also the liberal arts and fine arts” (pp. 6-7). In truth, technology education has always presented itself as “the great integrator” of disciplinary content and practice (Wells, 2012). As a discipline in and of itself, it is important to recognize that TEE is not STEM, nor is it STEM Education in general. Instead, it is a discipline that embraces the pedagogical responsibility of promoting knowledge integration through design based learning and recognizes this role as its unique contribution within the broader context of STEM education reform. This contribution occurs specifically through Integrative STEM Education, which serves as both the conceptual and pedagogical

¹ Wells/Sanders, Virginia Tech, January Program Flyer, 2008

framework for authentic design based integration of STEM content and practice. Integrative STEM Education is operationally defined as:

the use of technological/engineering-design-based approaches to *intentionally* teach content and practices of technology/engineering education concurrently with content and



practices of science and mathematics education. Integrative STEM Education is equally applicable at the natural intersections of learning within the continuum of content areas, educational environments, and academic levels (Wells & Ernst, 2012/2015).

As defined, Integrative STEM Education provides the pedagogical tenet of integrative practices where technological/engineering design based learning (T/E DBL) is the critical instructional requirement. Technology and Engineering is the discipline, and Integrative STEM Education is the pedagogical approach through which the content and practices of the discipline are taught.

The term “*integraTIVE*” implies an on-going, dynamic, student-centered process of teaching and learning. Conceptually this is distinctly different from an “*integraTED*” process which connotes a past-tense, static, pre-planned, teacher-centered pedagogical approach. An integrative strategy is therefore *dynamic* and supports active, open-ended, student-centered learning of STEM content and/or practice on a need-to-know basis in response to what is imposed by the design of a T/E solution. Design based learning is an instructional approach that uniquely engages the learner in arriving at a solution to an authentic, open-ended, design based problem scenario. The overarching context of the problem scenario is meeting a human need within as set of constraints specified by real-world criteria. *Technological/engineering design based learning* (T/E DBL) is the lead pedagogical strategy for I-STEM Education and therefore an instructional requirement. The instructional goal of I-STEM Education is to teach technology and engineering (T/E) content and practices as the target discipline, but with an equal focus on *intentionally targeting* other inherent content/practices (science, math, art, history, etc.) as additional learning outcomes students will achieve while engaged in the design of a solution. *The intent to teach other disciplines inherent to the design of a T/E solution is what distinguishes Integrative STEM Education from other pedagogical approaches.* Intentionality in teaching is paramount and requires alignment between learning outcomes. Furthermore, I-STEM Education operates along an educational continuum and at the natural intersects of learning. There is an overt effort to be *mutually inclusive* of other disciplines relative to the design of a T/E solution.

As defined, Integrative STEM Education does not apply solely to the STEM disciplines, is applicable in both formal and informal educational settings, and is appropriate at all academic levels.

3. Design to Understand

The U.S. Standards for Technological Literacy (STL) are explicit in their intent to have learners achieve understanding: "...students are expected to synthesize and apply information from other subjects as well as within the study of technology. In this way, they learn to make connections among different fields of study and begin to understand..." (ITEA/ITEEA, 2000/2002/2007, p. 9). Achieving student understanding, not merely demonstrating lower-order declarative or procedural knowledge, is the principal learning outcome to be attained through Integrative STEM Education. Student demonstration of understanding is accomplished by engaging them in T/E DBL where the instructional goal is explicit in "having students design to understand" when working toward the development of a viable engineering solution that meets a human need (Wells, 2016, pp. 14-15). Capitalizing on the inherent cognitive demands imposed on the learner while engaged in the design of a T/E solution, T/E DBL ensures that learners use higher order thinking as a requisite step toward the goal of understanding.

As a pedagogical approach, the principal goal of I-STEM ED is ultimately development of a student's cognitive capacity for responding to novel T/E DBL scenarios and their ability to make informed design decisions based on recognized connections among disciplinary content and practices. Among Technology and Engineering Education (TEE) scholars there is broad agreement that developing higher order thinking through I-STEM ED pedagogical practices is predicated on the Deweyan ideals of experiential learning; an experience where students are immersed in T/E DBL specifically to acquire those habits-of-hand (designerly abilities) that will intentionally lead to their developing the habits-of-mind (designerly ways of knowing) requisite of higher order thinking. This experience develops learners who are capable of informed decision making derived directly from their understanding of relationships between disciplinary content and practice. Simply stated, the principal goal of T/E DBL is development of the mind, where the hand and the doing are simply the scaffolding for learning and ultimately understanding.

Unique Ways of Knowing. Designerly ways of knowing (Cross, 1982) is an approach to acquiring knowledge that is unique to the T/E design based learning approach. An approach that

is fundamentally different from the traditional inquiry methods associated with the Scientific Method, Design Based Science (DBS), Problem Based Learning (PBL), and Project Based Learning (PjBL). The scientific method is a procedural method of acquiring knowledge that has characterized the development of natural sciences since as far back as the 17th century. It is a method consisting of systematic observation, measurement, and experiment with the goal of formulating, testing, and verifying and/or modifying stated hypotheses. It is typically presented as a linear series of steps one follows in an attempt to better understand a phenomenon. In the design of T/E solutions however, the scientific method is simply one of many inquiry tools the learner selects when acquiring knowledge through a designerly way of knowing. For example, as part of designing T/E solutions, scientific inquiry is the tool used by young learners when they need to conduct several small-scale scientific sub-experiments in order to answer questions such as “what materials demonstrate the best tensile strength and porosity for use as a semi-permeable membrane in the design of a microbial fuel cell?” Scientific sub-experimentation is part of the iterative requirement that T/E DBL naturally imposes on learners, which results in a continual need-to-know throughout all phases of design. Driven by this need-to-know, designing naturally demands that students draw on multiple STEM subjects as they oscillate between convergent thinking (what they know) and divergent thinking (what they need to know) when working to learn the content knowledge and practices needed to design the T/E solution. The designerly approach to acquiring knowledge is a pedagogical practice that is patently unique to Technology and Engineering Education. Demonstrating the development of the mind through designerly ways of knowing is often best brought to life within the presentation of classroom exemplars.

4. Exemplars of Integrative STEM Education

Integrative STEM Education has been used successfully in elementary, secondary, and postsecondary classrooms to teach the content and practices of TEE through design based learning. And although I-STEM ED may look different at any given school level,



Technology/Design Class



Canton Elem School

the same transdisciplinary principles apply to all ages and educational levels. For example, students at Canton Elementary School have been learning about TEE through topics as diverse as geometric shapes used in bridge building, ecosystems in the design of aquaponics systems, and

designing solutions to protect against environmental pollution prompted in their reading of Dr. Seuss' *The Lorax*. Similarly, I-STEM ED at the middle school level helps students learn through design challenges that target subject-specific standards of learning across several disciplines. This is the case at Blacksburg Middle School where sixth grade students tackle sustainability issues by researching, designing, and testing bioreactors that use immobilized microorganisms to generate ethanol as an alternative fuel. Or designing microbial fuel cells (MFC) in an attempt to create an alternative approach for generating electricity. Completing this biotechnical design challenge imposes on students an



authentic need-to-know the “life requirements” of the microorganism in order to know the “technological requirements” of the system (reactor) they want to design. The teacher capitalizes on this need-to-know by preparing her instruction in such a way to ensure students investigate the technology and biology content and practices she wants to intentionally target as learning outcomes for each subject.

At the postsecondary end of the learner spectrum, examples in higher education are found in graduate courses such as the design based biotechnology course (Wells, 2017) offered through the Integrative STEM Education graduate program at Virginia Tech. In this course, educators from all disciplines and teaching at all grade levels gain firsthand understanding, from the learner’s perspective, of the Integrative STEM Education strategies used in teaching disciplinary content and practices by being immersed in the research and construction of biotechnical solutions. For example, the course prepares educators to implement the middle school microbial fuel cell (MFC) challenge described above by engaging them in designing their own MFC. At



the conclusion of this design challenge each graduate student prepares a presentation to describe and explain their MFC as a means of demonstrating their Learned Outcomes. In doing so they each come to recognize, from the teacher’s perspective, how to design instruction that intentionally targets disciplinary content and practices by capitalizing on the student’s need-to-know as they construct and test a working prototype. Pedagogically, the instructional intent for using technological/engineering design based learning (T/E DBL) is to help students develop

those habits-of-hand necessary for promoting the habits-of-mind requisite to their use of higher order cognitive skills (Wells, 2010).

5. Our Students Design Your Tomorrow: Solving Wicked Problems

In the next half-century humankind will be confronted with global problems requiring solutions to highly complex social issues all of which have no discernable right or wrong answers. Problems such as these have been characterized as “wicked problems” (Rittel & Webber, 1973) referring to social system problems that are fundamentally ill-structured, involve information that is both confusing and conflicting, and for which there is no clear pathway leading toward a viable solution. In 2008 the U.S. National Academy of Engineering (NAE) announced what were identified as the 14 Grand Challenges for Engineering in the 21st century (<http://www.engineeringchallenges.org/>). The engineering challenges believed to be imminent for the current century will be more daunting than those that have occurred at any time in the past. Foremost among the challenges will be those that threaten the future of the planet as a result of global populations who are consuming its finite resources at a rate that is unsustainable and damaging global environments to the point of no repair. Growing concerns for sustainability are emphasizing the need for developing new sources of alternative energy while concurrently reversing climate change and preventing the degradation of the global environments. In particular, there is a growing imperative to better understand how societies can best learn to integrate across the natural and built environments in order to meet the growing demands for food, energy, and water while at the same time maintaining healthy global ecosystems. The integrative nature of the food, energy, and water ecosystems creates significant challenges for humankind to understand and manage the complexities of these interconnected systems today and far into the future. Meeting such grand challenges will require large-scale engineering solutions that are both economically and socioculturally feasible. More importantly, it will require individuals who are experienced in learning about complex problems through designerly ways of knowing and therefore possess the expertise and requisite cognitive capabilities necessary for developing viable solutions to wicked problems.



Individuals capable of solving tomorrow's wicked problems will be those who, at a young age, have received the type of education that prepares them to address ill-defined, ill-structured, open-ended problems. Technology and Engineering Education employs engineering challenges as an integral component of instruction. Immersing students in technological and/or engineering design challenges is a unique pedagogy that prepares them for acquiring STEM content and practice knowledge through designerly ways of knowing. This approach to teaching and learning equips students with the critical thinking skills needed to deal with the complexities of the 21st century grand challenges. Preparing students with these higher order thinking skills must begin early in their schooling. In the U.S. this preparation currently begins in middle school exploratory technology education courses for students in grades, 6, 7, and 8 (ages 11 to 14). An example of this type of preparation is found in how the *Inventions and Innovations* exploratory course being taught at a Virginia middle school incorporates the STEMbot as a platform for biotechnical design based learning.

6. Middle School STEM Exemplar

Students enrolled in the *Inventions and Innovations* Technology Education course at Blacksburg Middle School are learning to operate a programmable, computer numerical control (CNC), precision biotechnical robotics system called the STEMbot. Students progress through a series of ten



technological/engineering design based biotechnical learning (T/E DBBL) modules where they engage in biotechnical design challenges that build the STEM content and practice knowledge needed to ultimately design novel STEMbot tools and conduct biotechnical investigations. Specifically, the T/E DBBL modules challenge students with solving open-ended design problems that require their use of Cartesian coordinates to program STEMbot movements and tasks, take pictures with the STEMbot and use pixel-count analysis as a way to measure/chart plant growth, and use a 3D printer to create new STEMbot tools such as a misting tool for watering delicate seedlings. The modules culminate in a plant research challenge where students program the STEMbot to autonomously plant seeds, water plants, monitor/control environmental conditions (light, moisture, soil conditions, etc.) and investigate the impacts of variables such as the potential benefits of epiphytic bacteria.

The incorporation of STEMbot systems in middle school technology education programs is part of a larger, T/E DBBL collaboration between the Integrative STEM Education and Horticulture programs at Virginia Tech. The goal of the project is evidencing improvement of middle school technology education students' critical thinking skills, documenting their gains in STEM (science, technology, engineering, and mathematics) content and practice knowledge, as well as their increased STEM career awareness. Evidence of improved critical thinking skills is derived from student engagement in T/E DBBL via the STEMbot platform. The research project is designed as an iterative implementation study (repeated each 9-week instructional cycle) involving cohorts of both urban and rural middle school students (grades 6, 7, and 8) engaged in T/E DBBL modules embedded in the Virginia STEM Career Cluster (Advance CTE, 2019) *Inventions and Innovations* exploratory course. Comparisons of cohorts will reveal the extent to which the T/E DBBL approach influences learning outcomes across the full spectrum of middle school student populations and instructional environments. Results will add to understandings regarding the effects of a T/E DBBL approach on middle school students' critical thinking skills, their recognition of STEM career possibilities, and their motivation and preparedness for pursuing those careers during the crucial middle school developmental period of secondary education.

Research indicates that the middle school years constitute a pivotal developmental stage impacting the future educational and career directions of every student (Gottfredson & Lapan, 1997). Embedding T/E DBBL experiences in middle school Technology Education programs increases student awareness of STEM careers, motivates them to learn and connect disciplinary (STEM) knowledge relevant to pursuing those careers, and leads to the development of critical thinking skills required of the 21st century workforce. STEMbot, a precision biotechnical robotics system, serves as an instructionally flexible STEM learning platform providing T/E DBBL experiences that immerses students in designing, implementing, and evaluating authentic biotechnical applications. As an integrative STEM education exemplar, the STEMbot project reflects the unique curricular and pedagogical potential of Technology Education for positively influencing the development of those critical thinking skills students will need in any future STEM career they may consider.



7. The Potential of Integrative STEM Education

As a pedagogical innovation, there is great potential for Integrative STEM Education to affect significant change in teacher practice across all disciplines. Research on teaching practices does not support strategies that are either entirely student-centered or teacher-centered. What the research tells us is that using a blend of disciplinary teaching strategies through an integrative design based pedagogical approach is what best supports student learning. This is the basic premise of Integrative STEM Education (I-STEM ED) and teachers adopting this pedagogical approach are pressed to carefully reconsider their current teaching practices. The I-STEM ED type of instruction challenges teachers to reflect on what they do when teaching and why they chose to teach it that way. In reflecting they find themselves asking such questions as “What is the learning objective, how would a student demonstrate having achieved it, and is the strategy I chose to teach it a good one?” To be integrative, they then ask “What connections among the STEM subjects do I expect students to recognize and how should they demonstrate they are using those connections?” If the instruction does not explicitly teach to connections, it is very unlikely students will learn them. Teachers must be clear and focused in their design of instruction that will “intentionally teach” the content and practices inherent to the solution being designed, as this is what ensures students achieve deep understanding.

Reaching the full potential of I-STEM ED calls for both in-service and pre-service teacher professional development. Moreover, the professional development they receive must be the type that has a strong focus on the intentional teaching of STEM disciplines using T/E design based learning, where teaching is more than a series of activities and that what students learn is not left to chance. This approach to teacher development is not so much about educational reform, and much more about *Reformed Education*. Integrative STEM Education promotes *Reformed Education* in its call for and development of educators who are adequately prepared with the necessary pedagogical content knowledge needed to implement an approach where students design to understand.

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