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Views & Comments

Breaking the Silos of Discipline for Integrated Student Learning: A Global STEM Course's Curriculum Development

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1. Introduction

"In most classes, you're taught to learn it and you're not applying it to anything, so it doesn't stick." Francis Reyes, a student in Fairfax County's Global STEM Challenges course, sat on a stage with adults and professionals and explained how her STEM (which stands for science, technology, engineering, mathematics) course was different from others she had taken in the past. Unlike other courses, in STEM, Reyes said, "It's hands-on." Her principal, Pamela Brumfield of Edison High School, continued, "You give kids an opportunity to think outside the box and they will. We just have to create the opportunities for them" [1].

Creating inspiring, integrated STEM opportunities for students to learn science and mathematics in order to "make it stick" (i.e., make it memorable in the long term) is a daunting task. Often, teachers that specialize in science or mathematics are not specialists in engineering or technology education, so cross-over STEM teaching can result in one or more aspects of the STEM effort being minimized. For example, the science content may be minimized or the mathematical reasoning undermined when emphasis is placed on building something. However, cross-disciplinary planning partners for the Global STEM Challenges course have developed a curriculum that interweaves mathematics, science, and engineering to create a course in which the math and science are necessary to solve engineering challenges tied to the National Academy of Engineering (NAE)'s Grand Challenges for Engineering [2]. This paper describes the difficulty of designing a STEM-integrated curriculum, focusing especially on separations between the disciplines of science and engineering, and documents how Fairfax County's Global STEM course's curriculum overcame typically siloed disciplines to plan integrated STEM experiences for students. This paper does not explore *in situ* classroom enactment, but only the curriculum that was developed.

2. Issues with K-12 STEM integration

The full integration of engineering, technology, science, and mathematics is in tension with the more traditional separation of disciplinary content learning in schools. One possible reason is the enduring legacy of how engineering design is traditionally taught at the university level. The term "engineering design process" refers to "a systematic, intelligent process in which designers generate, evaluate and specify concepts for devices, systems, or processes [to] achieve clients' objectives [while] satisfying a specified set of constraints" [3]. Engineering design has specific attributes, such as analysis, constraints, modeling, optimization, and systems, within a highly iterative process [4], and requires certain engineering mindsets, including, for example, embracing multiple possible solutions [4], accepting the utility of productive failure [5], alternating and iterating through divergent and convergent thinking [6], and carefully monitoring progress toward goals and sub-goals.

Engineering has traditionally been taught in higher education, where engineering design is taught separately from the engineering sciences (e.g., fluid dynamics, electrostatics, physics, biochemistry, electrostatics, etc.) that comprise the bulk of engineering coursework [7,8]. This bifurcation has been blamed for higher education engineering students and graduates not understanding how content mathematics and science courses are connected to engineering practice and careers [9].

Separation between engineering instruction and science instruction has been reflected in K-12 course scheduling as well. Mathematics and science are required "core" courses, and engineering or technology education classes are optional "elective" courses. The requirements for each course including state-mandated testing, teacher preparation, and professional development are different. For example, the requirement to pass high-stakes tests in mathematics exists in all 50 states for high-school graduation, but no equivalent engineering design requirement has historically existed.

Yet the promise of integrated STEM learning has gained momentum in recent years, and various models of STEM learning have emerged, with different amounts of integration present. The popular K-12 engineering curricula Project Lead the Way (PLTW) continues the tradition of bifurcating core and elective courses by adding an additional PLTW course to the student's school day. Alternatively, the Next Generation Science Standards (NGSS) [10] emphasize that engineering design practices and science content should be learned simultaneously, acknowledging that "engineering [design] practices can develop as they are used in the classroom to help students acquire and apply science knowledge"

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[11]. This was a major shift away from the traditional separation, and it requires K-12 teachers to juggle the goals of teaching design processes and teaching science content concurrently.

A small body of research has shown that this is hard for teachers to do. It appears to be difficult to maintain an equal emphasis on science learning and on engineering design in practice. At times, the science may be relegated to a set of worksheets instead of being at the heart of a design activity [12], or the design process may be diminished, resulting in less-than-satisfactory design actions (e.g., tinkering or trial and error) to solve a challenge [13]. Another study on high-school physics teachers trying to teach integrated engineering lessons found that inadequate time was allotted to the engineering design process, resulting in inadequate data collection to drive engineering decisions and in an implicit de-emphasis of engineering design [14]. Using engineering design to teach science content means doing engineering design and content instruction together, but none of the studies described above found a successful balance between design and core content learning.

3. The Global STEM Challenges vision

In 2015, Fairfax County Public Schools submitted a High-School Program Innovations Planning Grant to the Virginia Department of Education to begin a new integrated STEM course at Edison High School in Alexandria, Virginia. The vision of the course was to provide students with a truly integrated STEM environment based on the NAE Grand Challenges for Engineering. Three teachers would team-teach 90 students for 4.5 h every other day. One teacher would be a mathematics content expert, one a science content expert, and one an engineering education expert.

The Global STEM Challenge course's vision for student learning was a three-part goal: ① to develop an understanding of engineering practices as they are used in the classroom, ② to teach new science and mathematics content, and ③ to apply previously learned science and mathematics knowledge. The student cohort would remain together for three years of high school: In Grade 9, they would focus on the Grand Challenges related to food; in Grade 10, they would focus on water challenges; and in Grade 11, they would focus on energy challenges. (See the approved grant application [15].)

Fairfax contracted the Knowles Teacher Initiative to assist in building the curriculum for this course. Knowles was selected because it had sponsored a team of Senior Fellow high-school mathematics and science teachers to develop a framework for teaching engineering within mathematics and science content areas and to practice their technique for over five years. Based on previous research, the Knowles leadership team was aware that the curriculum would have to balance core content acquisition with engaging engineering activities, so Knowles Senior Fellows with experience in STEM integration were hired by Knowles to pair with content experts from Fairfax to draft the curriculum. A three-day teacher workshop was held to orient the courses' teachers to the planned curriculum and to establish a shared vision of engineering design integration. Ongoing monthly collaborative meetings and site visits to the school ensured that the curriculum was taught with fidelity.

3.1. The Knowles engineering integration conceptual framework

The co-planned curriculum rested on a conceptual framework for engineering integration into mathematics and science that was developed by Knowles Senior Fellows (Fig. 1). The Knowles model conceptualized engineering design instruction as an iterative system of four intersecting and overlapping "phases" of engineering design: problem definition, design exploration, design optimization, and design communication.

The four phases of the Knowles model include the divergent-convergent aspects of engineering design. In addition, creative thinking, brainstorming, and an explicit emphasis on communication elevate the softer skills associated with engineering design [16]. Decision-making for design optimization requires students to use solid scientific processes and mathematical skills to make decisions about their design, instead of merely tinkering to find a way to success. The model is also intended to offer structure and support (i.e., possible beginning and end points along with scaffoldable pieces and relationships) for teachers who use it in classrooms.

4. Methods

The Fairfax County instructional leadership shared their vision with Knowles; this vision was also shared with the planners, along with the state content standards and a framework for presenting the daily lesson plans. Knowles Senior Fellows and Fairfax County teachers were paired to create six cross-content teams of planners. Inspired by Fairfax to orient the freshman year around the theme of food, each team selected a food-related Grand Challenge to frame science, mathematics, and engineering classwork around an engineering design challenge that the students would work on for approximately six weeks. Their task was to plan out each day, although they would not necessarily provide every classroom resource (e.g., worksheets or PowerPoint presentations) needed for instruction.

Through months of online collaborative effort, making heavy use of multiple-editor Google Docs, the planning teams established

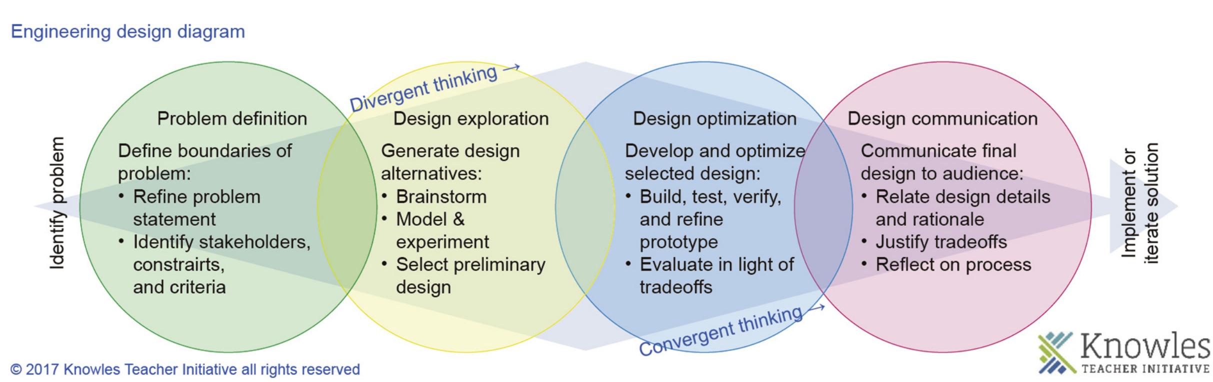

Fig. 1. The Knowles four-phase engineering design process model (©2017 Knowles Teacher Initiative).

essential questions for their units, daily learning targets, and daily plans for instruction. The Knowles Program Officer supervising the effort worked with Fairfax County Instructional Specialists staff to align the planned curriculum to state standards in order to ensure that over the three years, the students would have experiences in the content required by the state. The Fairfax County Instructional Specialists also helped to align the curriculum vertically to make sure that the incoming Grade 9 students would be prepared for the units, and to ensure that completing the units would prepare the students for future course work in Grade 12, after the students completed the three-year STEM Challenges course sequence.

5. Results and discussion: The Global STEM Challenges course

The six integrated STEM units that were developed for the freshman year of the course were centered on the following design challenges:

(1) Design a room plan for the unique multi-classroom setting of the Global STEM Challenges course.

(2) Design a portable microscope for field identification of pathogens on plant life.

(3) Design a therapeutic food and delivery system for the hungry.

(4) Design a greenhouse system to cultivate a specific food.

(5) Design a food waste system to minimize lost food and energy.

(6) Design a protein targeted at assisting individuals with lactose intolerance.

Each of these curricular units was intended to align with at least one of the Grand Challenges. Table 1 lists the Grand Challenges and the Grand Challenges' organizing themes represented in each Global STEM Challenges course Grade 9 unit.

Each unit was designed within the Knowles four-phase engineering design process (Fig. 1), emphasizing all aspects of the engineering design process. At the same time, the units bridged the usual stratification between engineering design and core content coursework by using the engineering challenge as the motivator for all classroom instruction. The units wove science, mathematics, and engineering design learning together by linking the sequence of the design process to science and mathematics content that would support it. For example, in the microscope challenge, students learned about the scale of pathogens and their function in the ecosystem in their science instruction; they then used that knowledge as a starting point to determine the necessary magnification of the microscope they were designing. At the same time, students learned about geometry and ratios related to magnification, angles, and triangles in ray diagrams in order to document their microscope designs appropriately, and learned about data analysis techniques in order to evaluate the effectiveness of their designs and make modifications. In technology class, students learned about proof-of-concept modeling and prototyping, computer-aided diagramming of the microscope design, and basics of balance and clarity in presenting their thinking in a public poster. The students worked in flexible groupings throughout the unit and improved their collaborative communication skills, creative problem solving, documentation, and reflection. They worked toward appreciating failure as moments of insight into an effective solution, and drew on the data they collected about their design in order to improve their design.

The complete instructional units are not in the public domain; however, Table 2 provides a snapshot of the interplay between science, mathematics, technology, and engineering that is present in each unit. (The chart only highlights the main content area emphases.)

The units were planned so that each curricular content area was necessitated by the engineering design challenge that the students would be working on. The relationships between the content strands were implicit at times and explicit at other times, with the intention that students would discover their own gaps in understanding as they worked through the design challenge, and would then be motivated to ask for the planned core content to help them devise, evaluate, defend, and communicate their design ideas.

Each unit revolves around a focus on "food." The curriculum included in each unit emphasizes biology and geometry concepts because they are traditionally the Grade 9 core science and mathematics courses, respectively. However, these units also integrate aspects of algebra, trigonometry, chemistry, physics, and computer science because they are inseparable aspects of thinking within the challenges' systems. Content area boundaries are further blurred as students learn traditional science content in their integrated mathematics strand, for example when lens diagrams and refraction are introduced through the mathematics strand in order to solve lens equations. Allowing cross-content connections to emerge allows the curriculum to remain focused on the challenge as the system of unit definition instead of on traditionally used disciplinary definitions. At the same time, each unit is layered with state learning standards to tether it to the demands of the state and the school. Identifying the standards present in the plans and seeking additional opportunities to include standards during planning helped to make the plans robust.

As a whole, the year's curriculum may be viewed as "spiraling" or moving between and among content areas—sometimes returning to previous content to explore it in a new way instead of moving step-wise through a year's curriculum in a steady progression. In this way, the curriculum plans for multiple exposures to the same content, but presents new applications for using that content. This structure may help to reduce the apparent disconnections that are frequently cited as occurring between students' science and mathematics learning and the applications of that learning to engineering practices and careers [8].

Table 1
NAE Grand Challenges and aligned Global STEM Challenges course Grade 9 units.

Global STEM Challenges course Grade 9 unit	NAE Grand Challenge(s)	
	Grand Challenge	Grand Challenges' organizing theme
(1) Design a room plan for the unique multi-classroom setting of the Global STEM Challenges course	• Advance personal learning	• Living and learning with joy
(2) Design a portable microscope for field identification of pathogens on plant life	• Engineering the tools of scientific discovery	• Sustaining life on Earth
(3) Design a therapeutic food and delivery system for the hungry	• Engineering better medicines • Restore and improve the urban infrastructure	• Sustaining life on Earth
(4) Design a greenhouse system to cultivate a specific food	• Manage the nitrogen cycle	• Sustaining life on Earth
(5) Design a food waste system to minimize lost food and energy	• Restore and improve the urban infrastructure	• Sustaining life on Earth
(6) Design a protein targeted at assisting individuals with lactose intolerance	• Engineering better medicines • Advance health informatics	• Sustaining life on Earth

Table 2
Global STEM Challenges course Grade 9 units and curricular emphases (© Knowles Teacher Initiative, 2017).

Global STEM Challenges course Grade 9 unit	Main mathematics content	Main science content	Main engineering/technology content
(1) Design a room plan for the unique multi-classroom setting of the Global STEM Challenges course	• Area • Composite figures • Scale • Ratios • Logic & proofs	• Nature of science • Observation & inference • Scientific investigation and data representation	Basic skills: • Problem definition • Criteria & constraints • Design alternatives • Technical drawing • Design process communication
(2) Design a portable microscope for field identification of pathogens on plant life	• Proportions • Magnification • Angles • Ray diagrams • Growth and decay functions	• Macroscopic and microscopic observation • Classification of living things • Cell theory • Lenses and refraction	Additional basic skills: • Stakeholders • Computer-assisted drawings • Design evaluation
(3) Design a therapeutic food and delivery system for the hungry	• Linear and quadratic functions and predictions • Optimization and solving systems of equations	• Energy • Energy and matter in the human body • Macromolecules	All of the basic skills above plus: • Propulsion • Wheel and gear ratios • Two-dimensional laser cutting • Three-dimensional modeling basics
(4) Design a greenhouse system to cultivate a specific food	• Rates of change • Unit conversions and ratios • Balancing ratios • Solving systems of equations • Exponential growth and logarithms • Efficiency	• Processing and cycling matter • Cell cycle • Photosynthesis • Chemical nomenclature • Stoichiometry • Cell transport • pH	All of the basic skills above plus: • Elevation drawings • Woodworking skills
(5) Design a food waste system to minimize lost food and energy	• Regular & irregular volumes • Surface area & volume • Percentages & efficiency • Absolute values • Graphical representations	• Climate change • Nitrogen cycle • Decomposition • Energy & carbon cycles & conservation • Respiration • Methanogenesis	All of the basic skills above plus: • Three-dimensional virtual modeling
(6) Design a protein targeted at assisting individuals with lactose intolerance	• Analyzing data • Analytic exponential models • Solving triangles, similarity, and congruency	• Cell functions • Gene expression • Genetics	All of the basic skills above plus: • Three-dimensional printing • Creating an infographic and product video

The success of the development of the units was dependent on the collaboration between the planners. Planning partners exploited their individual content expertise and engineering integration experience, and were thus able to help one another envision the unit as a whole and to assist in identifying the elements of traditional mathematics and science instruction that seemed pertinent to each unit.

6. Conclusions

The Global STEM Challenges course demonstrates a potential solution for how to interconnect traditionally isolated mathematics, science, and technology subject matter by engaging in engineering design challenges. Utilizing the NAE's Grand Challenges for Engineering as motivation and inspiration, the curriculum presents a way to frame mathematics and science learning in the context of engineering design. The curriculum development involved parties from the county, teachers of the course, and expert consultants who had experience teaching engineering integration in a core class. With an eye on standards and with experience in finding creative connections between traditionally separated courses, these planners invented a school-specific course that could fulfill the promise of using integrated engineering challenges to teach high-school mathematics and science.

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