Interdisciplinary STEM through Engineering Design-based Reasoning

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Abstract—Interdisciplinary STEM programs are in demand for United States middle schools (ages 11 to 13 years) and high schools (ages 14 to 18). The Real STEM Project collaborated with 12 schools to develop and implement such programs. We open with a description of the project, including the 21st century STEM reasoning abilities that were proposed as learning outcomes for the STEM programs. We then focus on one of the five reasoning abilities, engineering design-based reasoning, since engineering often serves as a driver for STEM programs. An exemplar of engineering design as a driver for STEM from one of the participating teacher's classrooms is provided, and a summary of teaching practices supporting interdisciplinary STEM is drawn from the example.

Keywords—interdisciplinary STEM, engineering design, STEM reasoning

1 Introduction

The call to establish STEM designated middle and high schools and create STEM academic/career pathways for future workforce development is a national trend [1]. The Next Generation Science Standards [2] and the Common Core State Standards for Mathematical Practice [3] provide science, engineering, and mathematical guidance that supports the inclusion of STEM in schools to prepare students to meet the grand challenges of the 21st century. We established the Real STEM Project to assist 12 schools in implementing STEM programs in their schools. High schools and feeder middle school partners developed and implemented interdisciplinary STEM courses. The tenets of the project were:

- Interdisciplinary STEM: incorporation of multiple areas of STEM into middle school connection courses and high school research courses
- Collaboration: establishment of interdisciplinary professional learning communities within the school and community partnerships with local STEM experts

- Authentic Teaching Strategies: instruction driven by project-based learning, problem-based learning, and place-based education strategies supporting student centric teaching
- STEM Reasoning: learning outcomes included 21st century reasoning abilities including complex systems reasoning, science model-based reasoning, technology computational reasoning, engineering design-based reasoning, and mathematics quantitative reasoning

Here we provide a quick overview of the Real STEM Project. We will then focus our discussion on one of the five STEM reasoning abilities that often serves as a driver for quality interdisciplinary STEM school programs: *engineering design-based reasoning*.

2 Real STEM Project

Tenet 1: Interdisciplinary STEM. Real-world problems are often ill-structured and complex, requiring an interdisciplinary approach comprised of unique skillsets from multiple disciplines coming together to develop possible solutions [4,5]. The Real STEM Project takes the perspective that a meaningful STEM task must incorporate at least two of the four STEM fields (Fig. 1), modeling for students the interdisciplinary nature of real-world problems [6]. This requires moving beyond teaching STEM in traditional content silos to adopting an interdisciplinary STEM perspective.

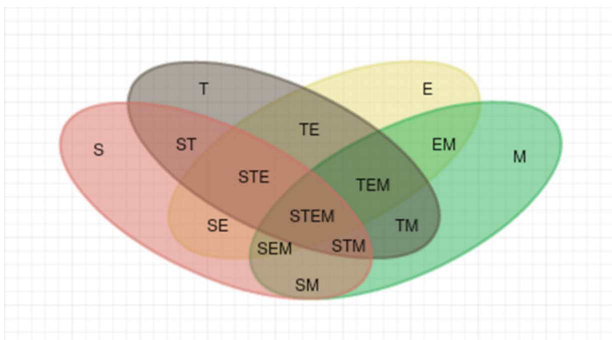

Fig. 1. STEM is interdisciplinary, occurring at the intersection of 2 or more of the STEM fields

Tenet 2: Collaboration. Interdisciplinary STEM requires a team approach to teaching in order to support authentic real-world ill-structured problems. Few teachers have all the expertise needed to address the different STEM aspects of such problems. Real STEM schools that were successful in implementing the STEM courses established interdisciplinary STEM learning communities that include teachers of science, mathematics, and engineering/technology, as well as administrators who meet regularly to consult on implementing STEM tasks. Furthermore, the development of expert support within the local community is essential to addressing authentic real-world ill-structured problems. This includes establishing STEM Advisory Boards consisting of local businesses representing multiple industries, research institutes, and government representatives.

Tenet 3: Authentic Instruction. Table 1 provides key elements of authentic teaching and learning that have the potential to increase student engagement and understanding of STEM [7]. A primary goal of STEM integration is to provide students with the opportunity to engage in real-world problem solving through hands-on experimentation, research, modeling, and design challenges. Broadening participation in STEM is best accomplished by moving towards more authentic teaching strategies characterized by student-centric practices that are project-based, problem-based, and place-based.

Table 1. Authentic teaching and learning design elements

Real-world relevance	Learning rises to the level of authenticity when it asks students to work actively with abstract concepts, facts, and formulae inside a realistic—and highly social—context mimicking how professionals conduct practice.
Ill-defined problem	Challenges cannot be solved easily by the application of an existing algorithm; instead, activities are relatively undefined and open to multiple interpretations, requiring students to identify the tasks and subtasks needed to complete the major task.
Sustained investigation	Authentic activities comprise complex tasks to be investigated by students over a sustained period of time.
Multiple sources and perspectives	Authentic activities provide the opportunity for students to examine the task from a variety of theoretical and practical perspectives, using a variety of resources, which requires students to distinguish relevant information in the process.
Collaboration	Authentic activities make collaboration integral to the task, both within the course and in the real world.
Reflection (metacognition)	Authentic activities enable learners to make choices and reflect on their learning, both individually and as a team.
Interdisciplinary perspective	Authentic activities have consequences that extend beyond a particular discipline, encouraging students to adopt diverse roles and think in interdisciplinary terms.
Integrated assessment	Assessment is not merely summative in authentic activities but is woven seamlessly into the major task in a manner that reflects real-world evaluation processes.
Polished products	Authentic activities culminate in the creation of a whole product, valuable in its own right.
Multiple interpretations and outcomes	Rather than yielding a single correct answer obtained by the application of rules and procedures, authentic activities allow for diverse interpretations and competing solutions.

Tenet 4: STEM Reasoning. The more student-centric and ill-structured a problem is, the more difficult it is to relate in advance to a particular STEM content standard. In fact, attempting to do so inversely impacts the open-ended nature of STEM tasks. We collaborate with teachers on anchoring their STEM tasks to process standards such as problem solving, critical thinking and reasoning. The learning outcome is the development of student ability to think like a scientist, a computer scientist, an engineer, and a mathematician. These experts have different problem-solving processes which, while they overlap, are not the same. We identified five STEM reasoning modalities we believe should be cultivated in students to prepare them for the challenges of the 21st century (Table 2).

Table 2. Twenty-first century STEM reasoning abilities

Complex system reasoning is the ability to analyze problems by recognizing complexity, patterns, and interrelationships within a system featuring a large number of interacting components (agents, processes, etc.) whose aggregate activity is nonlinear (not determined from the summations of the activity of individual components) and typically exhibits hierarchical self-organization under selective pressures [8].
Scientific Model-based Reasoning is the ability for students to construct scientific models in order to explain observed phenomena [9].
Technological Computational Reasoning is an analytical approach grounded in the computer sciences that includes a range of concepts, applications, tools, and skill sets that allow us to strategically solve problems, design systems, and understand human behavior by following a precise process that engages computers to assist in automating a wide range of intellectual processes [10,11].
Engineering Design-based Reasoning is the ability to engage in the engineering design process through implementation of a series of process steps to come up with a solution to a problem. Often, the solution involves designing a product (like a machine or computer code) that meets certain criteria and/or accomplishes a certain task [12].
Mathematical Quantitative Reasoning is mathematics and statistics applied in real-life, authentic situations that impact an individual's life as a constructive, concerned, and reflective citizen. QR problems are context dependent, interdisciplinary, open-ended tasks that require critical thinking and the capacity to communicate a course of action [13].

3 Engineering Design Task

3.1 Engineering Design Task Goals

So, what does engineering design-based reasoning driving interdisciplinary STEM look like in the classroom? One of our partner high school teachers provides the following example from her STEM classroom. The engineering design project her students worked on was building an electric car. The project was motivated by her students' interest in alternative energy sources powering a car. She guided the students in using an engineering design process to establish goals, criteria, and constraints for the design project. Several general goals help guide the electric car unit, including:

- Building comprehension of electric versus gas platforms and their environmental impact
- Measuring how far the completed electric car can go in 60 minutes on a track
- Engaging in trial and error to determine the efficiency of different driving methods, such as coasting versus using the throttle

3.2 Materials

The electric car kit was supplied by Coastal Electric Cooperative through their "Round Up" program. This community partner is a power company located in southeast Georgia. The program asks existing customers to round up their power bills to the nearest dollar. The excess money is deposited in a fund meant to support local education initiatives. The established partnership between Coastal Electric Cooperative and local schools reflects the importance of developing STEM advisory boards and collaborating with local professionals and businesses. For instance, during the electric car unit, a participating electrician was brought in to assist with the wiring of the car. Through professional collaboration with community members and businesses, students gain firsthand exposure to professionals working in the field. This helps showcase to students the different ways in which what they learn in the classroom can be used out in the community.

3.3 Lesson Plan Overview

The electric car unit is student directed with the teacher acting as a guide to stimulate conversation and research. The students are encouraged to research the design and function of each part of the car and determine how the different systems come together. Students are broken up into teams assigned to different objectives. As part of the assignment, students must incorporate their collective knowledge of differing subjects, such as physics, engineering, and mathematics. Throughout the course of the project, student strengths became apparent and were utilized by the group. For instance, some students excelled at understanding blue prints and used that knowledge to wire the car, while other students excelled at tool-work and modification. This setup emphasized for the students the importance of interdisciplinary cooperation to address complex tasks.

The teacher's role during the project is to serve as a guide to stimulate discussion and spur creative problem solving. Prior to beginning the module, the teacher introduced the concept of engineering-design and reviewed with the students the systems required for the car, such as the electrical system, mechanics of the drive system, and integrating these systems with the frame of the car. Furthermore, the teacher defined any necessary terms and encouraged critical thinking as to any potential additional goals for completing the car. The teacher also introduced the concept of renewable energy and explored the applicable differences between electric power and gas power.

3.4 Timeline

As part of the introduction to the module, the students and teacher collectively developed a timeline to ensure completion of the project. It is important to structure the timeline so that there is room for unplanned problems and solution-development.

During the 1st semester, students were responsible for understanding the design and function of the different components of the car. This included laying out and grouping the different parts and considering the best way to tackle the build. As building began, students were tasked with drilling the necessary holes, beginning to assemble the necessary pieces, and identifying any manufacturing defects to be corrected.

During the 2nd semester, students begin by reviewing what was done during the 1st semester. The design and build were reviewed for any mistakes or previously missed manufacturing defects and students were tasked with exploring solutions. Furthermore, students during the 2nd semester were charged with understanding and wiring the electronics. To assist in wiring the car (the most challenging part of the project), it is strongly advised to have students keep notebooks documenting the process and its steps, keeping electronic schematics and recording data output during the testing phase.

Students embraced the student-directed nature of the project to formulate their own short-term timelines and group objectives for the project. For example, Fridays were used for teams of students to meet and structure objectives and strategies for the following week. This required students to breakdown the electric car unit into small, obtainable steps throughout the project, in line with one primary tenet of engineering-design. This also required the incorporation of time management skills to meet the projects objectives (a complete car) while working within its constraints (limited time frame), two identified goals of engineering design in the classroom.

3.5 Areas to Improve

As with any engineering task, obstacles encountered will often involve a mixture of manufacturing errors and level of expertise. The electric car unit was no different as students encountered both, requiring creative problem solving, collaboration with professionals, and redesigning of the car, all of which capture the engineering design process.

Students quickly discovered during the first semester of the unit that the supplied battery did not fit in the battery box because of the overlaying seat pan. Students were tasked with reviewing the structure and integrity of the seat pan and developing possible solutions to the problem. Solutions included relocating the battery, using a smaller battery, or modifying the seat pan by cutting notches for the battery to fit. The team of students assigned to the problem decided that there was no other location to relocate the battery, nor did they want to sacrifice power or life of the battery by reducing its size. Students elected, instead, to modify the seat pan by cutting notches to create the needed extra space. The process of creative thinking, consideration of solutions, and the redesign of the seat pan were meticulously documented and sketched in the student notebooks.

It was also discovered while wiring and testing the vehicle that the throttle's output was too high compared to the supplied specifications that came with the kit. A team of students was tasked with reviewing the purpose of a throttle, its effect on other working components of the vehicle, and possible causes and solutions to the problem. In addition, the problem required students to collaborate with the school's engineering teacher who was not part of the project, as well as professionals in the community with experience dealing with automotive parts and electric platforms. After careful consideration the students discovered the problem to be a notch inside the throttle body which required turning 180 degrees.

3.6 Closing the Unit

After completion of the electric car unit, students and the teacher reviewed the engineering process, the successes of the unit, and areas for future improvement. As part of the closing, other schools completing a similar task collaborated in the discussion. Students reported an overall positive experience and especially enjoyed the student directed nature of the unit. The teacher's role at this time was to review the engineering design aspects with the students, including the core ideas and the process from conceptualization to completion, while tying the unit to real world phenomena and grand challenges. Specifically, the electric car unit emphasizes the role of vehicles in climate change and possible grand solutions to the problem. Examples of questions asked at the beginning of the project, such as the carbon footprint of electric versus gas platforms, helped to guide the unit and were summarized and debated by students at closing. Students were also asked to consider what other areas of STEM were present during the unit, such as scientific model-based reasoning and quantitative reasoning. The goal being to emphasize to students, in their own words, the interdisciplinary nature of real world problems and their solutions.

The final performance task for the engineering design process was a presentation to a panel of experts and demonstration of the car on a track laid out in the school parking lot. Incorporation of a performance task where students demonstrate their understanding of concepts is an essential component of authentic teaching and learning.

4 Conclusion

Not all teachers will have the resources or time to let students build an electric car, but the teacher displayed a number of practices that should be considered on any engineering design task. In our work with partner schools we often saw engineering design invoked as a means of engaging students in science or mathematics classes. Too often the implementation of the design task lacked teaching practices that truly engaged students in the design process and incorporated interdisciplinary STEM learning. Here are several teaching practices the teacher implemented to ensure the design task was more than engaging activity, ensuring that the task engaged students in STEM reasoning.

- Student centric: The task was motivated by her students' interest, not assigned by the teacher. Increased engagement comes from moving from project-based learning directed by the teacher to problem-based learning and place-based education practices that leave space for the student to have input on the problem.
- Explicitly teach design process: Guide students in using an engineering design process to establish goals, criteria, and constraints for the design project. The omission of criteria and constraints from the design process may save time, but it leads to trail-and-error strategies where students copy others designs.
- Teacher as guide: The teacher acts as a guide to stimulate conversation and research by the students. Allow students to struggle with the design and redesign phase of the design process, this is where creativity and problem solving arise.
- Collaboration with STEM experts: Reach out to community STEM experts and have them serve as mentors, collaborators, and evaluators of the final product resulting from the design task. Have students present the product of their design effort to a panel of experts, demonstrating how the product solves the design problem.

- Professional Learning Communities (PLC): Form interdisciplinary STEM professional learning communities within the school. This supports interdisciplinary aspects of STEM and provides opportunities to spread STEM integration into other classes.
- Cooperative learning: Group students into design teams to work on the task. This provides for brainstorming and increases soft skills of collaboration and communication.
- Project timeline: Students and teacher collectively developed a timeline to ensure completion of the project. Student-directed nature of the project allows students to formulate their own short-term timelines and group objectives for the project. Incorporate time management skills to meet the projects objectives while working within its constraints.
- Engineering design notebooks: Have students keep notebooks documenting the design process and its steps, keeping electronic schematics and recording data output during the testing phase.
- Redesign: Often we saw time constraints on the design task result in dropping the redesign step of the design process. This leads to one-shot trial-and-error designs. Engineering requires redesign to meet criteria and constraints, as well as improve the product. Make time for redesign.
- Reflection on process: When the design cycle has been completed, have students and the teacher review the engineering process, the successes of the unit, and areas for future improvement. The teacher's role at this time is to review the engineering design aspects with the students, including the core ideas and the process from conceptualization to completion.
- Interdisciplinary STEM lenses: Have students consider what other areas of STEM were present in the design of the solution, such as scientific model-based reasoning to explore the science underlying students' designs and quantitative reasoning to provide data supported evidence of the efficiency of the design. Too often we saw engineering design tasks that missed the opportunity to be interdisciplinary by avoiding viewing the problem from a science, technology and mathematics perspective.
- The teacher implementing the electric car design task is a chemistry teacher. She was not formally trained in engineering. She sought STEM expertise from others as needed and was not afraid to say, "I don't know the answer to your question, but let's work together to find out". Teaching interdisciplinary STEM requires teachers who are willing to go outside their area of expertise and give students the opportunity to take charge of their own learning.

5 References

[1] President's Council of Advisors on Science and Technology. Prepare and inspire: K-12 education in science, technology, engineering, and math (STEM) for America's future. 2010.

[2] Next Generation Science Standards. Next generation science standards: For states, by states. Washington, D.C.: The National Academies Press, 2013.

[3] National Governors Association Center for Best Practices, Council of Chief State School Officers. Common Core State Standards Mathematics. Washington DC: NGAC, CCSSO, 2010.
[4] D. H. Jonassen. "Instructional design models for well-structured and ill-structured problem-solving learning outcomes. Education Technology Research and Development, 45, 1, 65-94. 1997. https://doi.org/10.1007/BF02299613
[5] J. R. Savery. "Overview of problem-based learning: Definitions and distinctions." In C. E. Hmelo-Silver, H. Leary, & A. Walker (Eds.), Essential Readings in Problem-based Learning (5-15). West Lafayette, Indiana: Purdue University Press, 2015.
[6] M. M. Capraro & Jones M. "Interdisciplinary Stem Project-Based Learning." In R. M. Capraro, M. M. Capraro, & J. R. Morgan (Eds), STEM Project-Based Learning. Rotterdam, The Netherlands: Sense Publishers, 2013. https://doi.org/10.1007/978-94-6209-143-6_6
[7] M. Lombardi. Authentic learning for the 21st century: An overview. EDUCAUSE Learning Initiative (ELI), 2007. Retrieved from https://library.educause.edu/ resources/ 2007/ 1/authentic-learning-for-the-21st-century-an-overview.
[8] J. H. Holland. Complexity: A Very Short Introduction. New York: Oxford Press, 2014.
[9] C. Schwarz. A learning progression of elementary teachers' knowledge and practices for model-based scientific inquiry. Paper presented at the annual meeting of the American Educational Research Association, San Diego, CA, 2009.
[10] U. Wilensky, and M. Resnick. "Thinking in levels: A dynamic systems perspective to making sense of the world." Journal of Science Education and Technology, vol. 8, no. 1, 1999, 3-19. https://doi.org/10.1023/A:1009421303064
[11] J. M. Wing. Computational thinking. Communications of the ACM, vol. 49, no. 3, 2006, 33-35.
[12] D. L. Householder, and C. E. Hailey. "Incorporating engineering design challenges into STEM courses." National Center for Engineering and Technology Education, 2012. Retrieved from: http://ncete.org/flash/pdfs/NCETECaucus Report.pdf.
[13] R. Mayes, J. Forrester, J. S. Christus, F. Peterson, and R. Walker. "Quantitative reasoning learning progression: The matrix." Numeracy, vol. 7, no. 2, 2014.

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