

The 21st Century STEM Reasoning^{*}

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The integration of Science, Technology, Engineering, and Mathematics (STEM) programs within the educational framework and the creation of STEM-designated schools and academic/career pathways represent a national trend meant to prepare students for the demands of the 21st century while addressing future workforce needs. Often, however, the STEM disciplines are taught within silos independent of each other. Students miss the opportunity to participate in the interrelationship among the STEM disciplines, resulting in missing opportunities to build critical reasoning skills. The Real STEM Project focuses on the development of interdisciplinary STEM within the school and community. Interdisciplinary STEM is characterized by sustained professional development that is job-embedded and competency-based, and on the development of student reasoning abilities across contexts. To accomplish this, interdisciplinary STEM should strive to be inclusive when it comes to the multiple STEM disciplines, embrace authentic teaching strategies that are based on real-world problem-solving through hands-on student engagement, and structured around the three Ps: project-based, place-based, and problem-based. To assist in developing an interdisciplinary STEM program, this article concludes with a focus on five primary reasoning modalities that best capture the spirit of interdisciplinary STEM: complex systems reasoning, science model-based reasoning, technology computational reasoning, engineering design-based reasoning, and quantitative reasoning.

Keywords: interdisciplinary STEM, reasoning, authentic teaching, expert collaboration

Introduction

The integration of Science, Technology, Engineering, and Mathematics (STEM) into schools is a national trend, apparent in the call to establish STEM designated middle and high schools (President's Council of Advisors on Science and Technology, 2010), as well as in the creation of STEM academic/career pathways for future workforce development (National Science Board, 2015). The Next Generation Science Standards (NGSS, 2013) and the Common Core State Standards for Mathematical Practice National Governors Association Center (2010) provided science and engineering practices and mathematical practices that support the inclusion of STEM in schools. These practices include modeling, integrating mathematics and computational thinking into science, planning and carrying out investigations of real-world problems, analyzing and interpreting data, and designing solutions. So, how do educators trained in one area of STEM incorporate it into their schools and classrooms?

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One essential component is sustained professional development in interdisciplinary STEM. Sustained professional development is job-embedded and competency-based, and aims to build interdisciplinary professional learning communities that include school administrators and teachers of TEM. In designing an interdisciplinary STEM program, it is essential to provide support and mentoring for teachers in the key tenets of STEM teaching and learning, including:

1. Ensuring that STEM is taught as an interdisciplinary approach;
2. Incorporating authentic teaching strategies;
3. Creating STEM community, business, research institute, and school partnerships;
4. Setting outcomes that go beyond student engagement to development of STEM reasoning.

Here, we discuss the Real STEM Project which was designed to actively engage schools in these tenets.

Real STEM Program Key Tenets

The four tenets of the Real STEM Project are essential to implementing interdisciplinary STEM: interdisciplinary STEM inclusion, authentic teaching strategies, community collaboration, and reasoning outcomes.

Interdisciplinary STEM Inclusion

We take the perspective that a meaningful STEM task must incorporate at least two of the four STEM fields (see Figure 1). In our work with schools, we see teacher's challenged to reach beyond their area of expertise to implement interdisciplinary tasks. We see a lot of S & M and not as much T & E. We ask teachers to have students view problems through all four STEM lenses, eliminating those that do not apply. Real-world problems are interdisciplinary, often requiring complex systems thinking. This requires moving beyond teaching STEM in traditional content silos to taking an interdisciplinary STEM perspective. We also need to move beyond the traditional science paradigms of experimental science and theoretical science to include computational science and data-intensive science (the T in STEM).

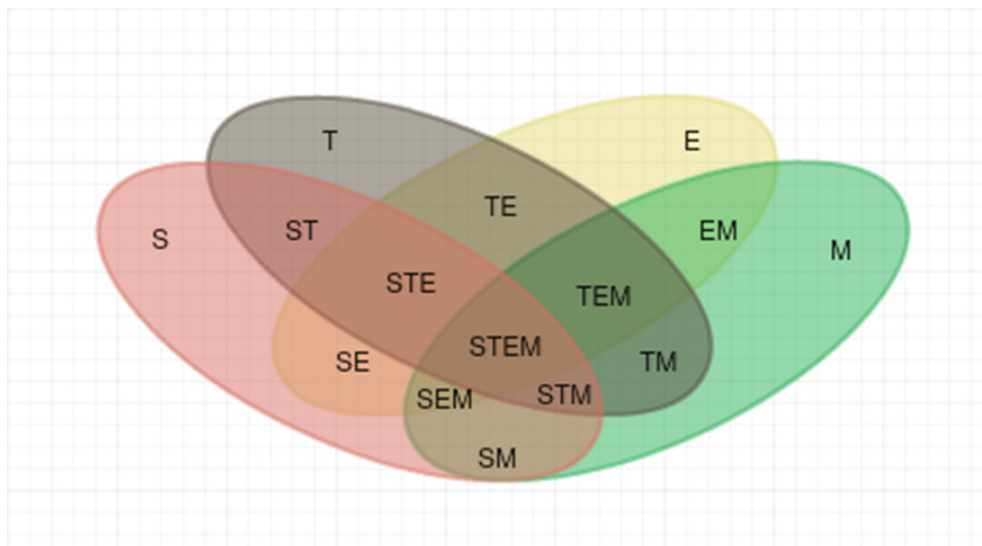


Figure 1. STEM is interdisciplinary, occurring at the intersection of at least two STEM fields.

Authentic Teaching Strategies

A primary goal of integrating STEM into a school 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 student-centric practices, and moving away from the traditional teacher-directed classroom. We mentor teachers in implementing authentic teaching strategies including project-based learning, problem-based learning, and place-based education.

We found project-based learning to be a good initial step in implementing authentic teaching strategies. Project-based learning allows the teacher to remain in control of assigning the task, such as this Real STEM, teacher engaging students in engineering water bottle rockets (see Figure 2). Project-based learning allows for inclusion of five authentic learning elements: (a) student collaboration through small group design teams; (b) sustained investigation; (c) reflection on learning; (d) interdisciplinary approaches; (e) integrated assessment through a performance task demonstrating understanding; and (f) polished final products. Teacher-assigned projects allow the teacher to target specific science concepts. However, this potentially restricts addressing three other desirable authentic learning attributes, including: (a) ill-defined, more open-ended problems; (b) requiring research into multiple sources and perspectives; and (c) diverse interpretations and outcomes.



Figure 2. Project-based learning: Engineering water bottle rockets.

Problem-based learning can potentially incorporate all nine of the authentic teaching attributes listed above, if teachers allow student input on selection of the problem. The more student-centric the problem selection is, the greater the potential engagement of the student. For example, a real STEM teacher had students brainstorm potential STEM projects. The students chose the problem of building a full-scale electric car powered by a solar panel (see Figure 3). The students formed teams to work on different components of the car. The car is currently underway using battery power, though they were still working on incorporating the solar panel. Student selected problems can potentially come at the cost of targeting specific STEM concepts, since the problem drives what is studied. In response, learning outcomes need to shift from content understanding to process abilities, such as reasoning and problem-solving.

Place-based education incorporates authentic teaching attributes one through nine, embraces a student-centric focus, and motivates another attributes: real-world relevance tied to student's locale. Students work within a realistic, social context related to their local place, providing the opportunity for a maximum student-centric experience. We explore with teachers grand challenges within STEM fields identified by

national/international experts, such as the eight grand challenges of environmental science (National Research Council [NRC], 2001). Students connect the challenges to their locale and identify problems they would be interested in studying, following the call to “think globally, act locally” in environmental science. The problems are vetted through student peer mentors, the teacher professional learning communities, and community STEM experts. One of our Real STEM schools chose the grand challenge of hydrological forecasting. They revitalized a pond on the school property, studying parking lot drainage issues and the pond ecosystem (see Figure 4). The teacher professional learning communities in our partner schools have incorporated grand challenge problems into existing classes through STEM Fridays (dedicating a day to STEM) or by developing new STEM courses.



Figure 3. Problem-based learning: Designing an electric car.



Figure 4. Place-based education: Revitalizing a pond near the school.

Community Collaboration

Interdisciplinary STEM requires a team approach to teaching in order to support authentic real-world ill-structured problems. Few teachers have the expertise to address different STEM aspects of such problems.

1. Teachers have to be comfortable with not knowing all the answers, and to be confident in saying, “I do not know, but let us work together to find out”;

2. A strong teacher professional learning community is essential in providing expertise from multiple STEM areas. Real STEM schools established interdisciplinary STEM learning communities that included, at-minimum, teachers of STEM, and an administrator. The professional learning communities met regularly to consult on implementing STEM tasks;

3. Development of STEM community expert support is essential, including establishing STEM Advisory Boards consisting of business, industry, research institute, and government representatives. We explore a continuum of support levels with our participating partners: low intensity (guest expert and field trip), moderate intensity (mentor, STEM problem/challenge, and funding STEM materials/supplies), and high intensity (teacher externship, student internship, and funding STEM professional development);

4. The Real STEM Project hosted field trips for teachers to interact with STEM experts from areas as diverse as agriculture, energy, and ocean science (see Figure 5).



Figure 5. Teacher field trip on the NOAA research vessel RV Savannah, sailing out of Skidaway Institute for Oceanography. Teachers assist scientists with count from a trawling run.

Reasoning Outcomes

For interdisciplinary, STEM programs to grow and be sustained they must have established learning outcomes. What are the standards addressed by a STEM experience? What does STEM do for our science and mathematics test scores? We identified five STEM reasoning modalities which are 21st century abilities students should develop (see Figure 6).

The more student-centric and ill-structured a problem is, the more difficult it is to tie in advance to a given STEM content standard. In fact, attempting to do so inversely impacts the open-ended nature of STEM tasks. We collaborate with teachers on tying their STEM tasks to process standards. The learning outcome should be 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.

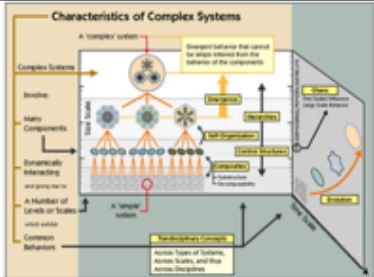
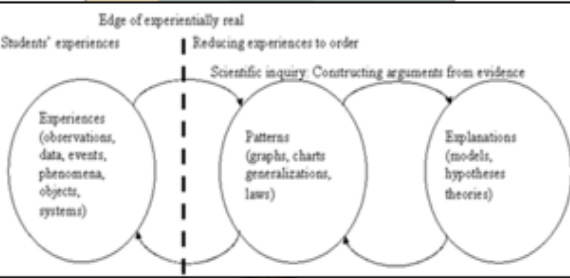
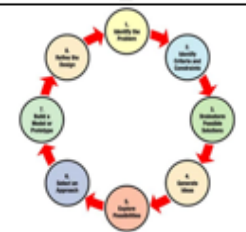
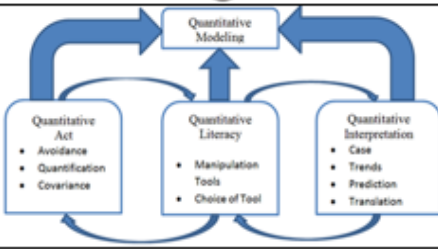
STEM Reasoning Modality	Visual Representation
Complex system reasoning is the ability to analyze problems by recognizing complexity, patterns, and interrelationships within a system featuring a large number of interacting components (agents, processes, etc.) whose aggregate activity is nonlinear (not determined from the summations of the activity of individual components) and typically exhibits hierarchical self-organization under selective pressures (Santa Fe Institute).	
Science Model-based Reasoning is the ability for students to construct scientific models in order to explain observed phenomena (MUSE).	
Technology 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.	
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. Many times the solution involves designing a product (like a machine or computer code) that meets certain criteria and/or accomplishes a certain task.	
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.	

Figure 6. STEM reasoning modalities and visual representations.

Conclusions

The Significant Results

The Real STEM Program found several successful outcomes and documented areas needing improvement. Teacher focus group interviews indicated they understood and were enthusiastic about implementing the four tenets of the program. Teachers' level of concern, confidence, and commitment in implementing STEM significantly improved in five areas: collaboration with STEM experts, using authentic instruction, teaching for understanding, teaching interdisciplinary STEM, and incorporating STEM reasoning into tasks. The challenges

reported by the STEM lead teachers included teaching STEM reasoning abilities outside their area of expertise, professional learning community collaboration, and varying levels of administrative support. We found that middle school structure supported implementation of STEM, due to cross-discipline teams and the existence of eighth grade transition courses that could be dedicated to STEM. However, it was more difficult for high schools due to the isolation of high school subjects into silos and the necessity of creating new STEM courses, a challenge for districts stretching to meet required program demands. Expansion of the STEM programs was dependent on the level of administrative support, with some programs expanding rapidly to multiple course sections and others remaining as one course championed by a teacher.

Students participating in the Real STEM experience reported positive attitudes about STEM, with statistically significant improvement in intrinsic motivation (4.27 on 5 level scale), self-management/self-regulation (4.21), and persistence in STEM (4.02). They held positive attitudes about both problem-solving (4.08) and exposure to active learning through hands-on tasks (3.85). Students on both the middle and high school levels, as well as male and female, had statistically significant improvement in interest in all four areas of STEM (4.00), confidence to do well in school (3.93), importance of understanding STEM (4.12), interest in taking STEM classes (3.83), interest in STEM career (3.46), interest in college STEM degree (3.58), importance of being STEM literate citizen (4.02), understanding interdisciplinary connects in STEM (4.26), comfortable dealing with complex real-world problems (3.93), and enjoying STEM (4.17).

A STEM reasoning abilities assessment was developed to provide a common measure for student understanding of the five 21st century reasoning modalities. The assessment consisted of 34 multiple choice questions. The assessment was voluntary and was not given by all the participating schools, due to not all schools addressing all five reasoning modalities. A total of 868 students took the assessment. On the middle school level overall there was a drop in reasoning assessment scores, while at the high school level there was an increase in scores. A smaller group of 199 students from two middle schools and two high schools completed both a pre-assessment and post-assessment. Overall the middle schools did not show statistically significant improvement on the STEM reasoning assessment, but the high schools did. On both the middle and high school levels, one of the two schools demonstrated statistically significant improvements on the reasoning assessment. Schools demonstrating improvement explicitly engaged students in modules on at least four of the five reasoning modalities.

School and Teacher Takeaways

Schools and teachers implementing STEM programs can take the following away from our Real STEM Project experience.

1. Interdisciplinary STEM professional learning communities are critical to the success of your STEM program. Interdisciplinary STEM teaching requires experts from multiple areas;
2. Administrative level support for STEM is essential if the program is to grow beyond dedicated first-adaptors. Develop a school wide STEM plan and provide time for professional learning communities to jointly plan curriculum;
3. Develop community STEM partnerships that encourage place-based real-world problem-solving and provide regional experts to partner with teachers;
4. Authentic teaching strategies are paramount to engaging students in authentic STEM problems. Interdisciplinary STEM requires a change in teacher practice;

5. Set appropriate learning goals for your STEM program which focus on process abilities, such as reasoning and problem solving. Move beyond engaging activities to authentic tasks.

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