Rethinking STEM in the Elementary Grades

Honoring the Special Role of Math in Cognitive Development

By Douglas H. Clements and Julie Sarama

There is a growing interest in STEM (science, technology, engineering, and mathematics) units and projects in the early childhood and elementary years.[1] As former teachers turned researchers, we welcome this nascent movement, but because of our experience we suggest reflection and caution—particularly regarding the role of math in STEM education. There are many advantages of embedding math in STEM contexts and activities; it can be excellent for reinforcing math (as well as science, technology, and engineering) concepts and skills. However, there may be unintended problems. Especially if the core attributes of the disciplines are not respected, students can become overloaded with the number of new STEM concepts, and essential domain-specific content may be missed. We provide an alternative interdisciplinary approach that maintains the positive aspects of STEM through careful integration while minimizing the possible negatives by focusing on the content that students most need to master. Math is at the top of that list.

The Role of Mathematics

Arguably, math plays a central role in the sciences. Throughout the world, almost every STEM advance (from more efficient solar energy to telescopes that probe deeper into the universe) is expressed in the language of math. And throughout schooling, mathematical development is central not only to STEM but also to overall school success. For example, the more math courses students take in high school, the higher their performance in college math, biology, chemistry, and physics courses. In fact, taking more high school *math* courses increases achievement in the sciences as much as, or even more than, taking more science courses![2]

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ILLUSTRATIONS BY ENRIQUE MOREIRO

Perhaps more surprisingly, high-quality math learning may contribute to students' development of reading,[3] language,[4] social competencies,[5] and executive function.[6] It's also the best predictor of graduating high school.[7] High-quality math experiences always encourage students to answer questions such as "How do you know?," What is your strategy?," and "Can you prove that?" Students have to dig deeply, metacognitively (thinking about their own thinking), to answer such questions, building both language and executive function competencies. Even everyday word problems help develop language and executive function. Reading, "There are six birds in a tree. Three birds already flew away. How many birds were there from the start?," students have to inhibit the immediate desire to subtract engendered by the phrase "flew away" and instead figure out the sum six plus three.[8] This need to inhibit the first impulse to answer and carefully examine the problem might be a key reason why math contributes so much to later achievement in all subjects, including science. Such inhibition is an essential part of well-developed executive function, and executive function is the best predictor of later science achievement.[9] Given that math is important in itself *and* appears to support learning across so many other domains (including general thinking skills), we conclude that *math is a core component of cognition*.[10]

This is not to say educators should focus more on math; indeed, the STE of STEM deserve more time in school. The answer to that may lie in recognizing that literacy/reading is often the "curriculum bully"[11] and time is better spent developing reading and writing in the service of STEM investigations.[12] What we *are* saying is that time on math may increase but more important is that the *quality* of math teaching and learning increase.

Establishing Truth: STE vs. M

Along with its unique contribution to learning across domains, math differs from science, technology, and engineering in how it establishes "truth." Validity in math comes from logic, reasoning, and proof—it is *within the structure and content of mathematics* and thus develops and processes within one's mind. Validity in STE comes from the scientific testing of ideas and theories in the world and a social consensus about the results. Preschoolers implicitly learn these knowledge foundations when given the opportunity. For example, about 15 years ago, we were in the first preschool classrooms to pilot our learning trajectories approach to teaching and learning math,[13] in which we determined how to sequence math topics to be in step with how most children develop their mathematical understandings. In a geometry activity, one four-year-old said to another, "You don't have to ask the teacher. Triangles have three sides connected. This one is really skinny, but it's *got* that. It has to be a triangle!"[14] In the same classroom, the teacher recorded a long discussion of an engineering project, ending with, "We don't know if this design is the best. We need to test it." This is a fundamental difference: justifying a math idea comes from reasoning and proof in one's mind, whereas justifying a science or engineering idea requires supporting empirical evidence.

This fundamental difference between STE and M has implications for instruction. Some attention to math *qua* math, emphasizing *argumentation* as the way to determine the truth of ideas, is needed. And attention to science, technology, and engineering is needed for students to learn about empirical truths.

By now, our concerns about STEM should be starting to emerge. We want to be sure that nothing interferes with students learning math or with them understanding the fundamental differences between math and the sciences. Do STEM units and projects interfere? Not necessarily, but they can—especially given limited instructional time and all the competing needs that elementary teachers must meet.

STE+M

To better understand our concerns, particularly of math getting lost in STEM projects, let's look at a few examples—starting with STE and adding M. Science, technology, and engineering are a tight domain group, especially since technology and engineering put science to work, ideally for the good of humanity and the planet. And engaging students in STE projects can be an excellent way for them to learn about each discipline while also learning core content. For example, in fifth grade, students might engage with a unit developed by Youth Engineering Solutions* called Engineering Plastic Filters.[15] This unit highlights how plastic pollution can affect organisms in marine ecosystems. It challenges students to design a filter to reduce the amount of plastics entering the ocean. The unit integrates life science, earth science, and engineering performance expectations and focuses on environmental engineering. Comics introduce the problem as well as the scientific ideas that students will explore during the lesson. For instance, in one comic, characters ask how a fish could get sick from a water bottle. They call a scientist, who explains that plastic breaks down over decades into teeny pieces, called microplastics, that fish ingest. Following a model of engineering design, students pose questions, then turn to imagine, plan, create, and test filter solutions that might clean water coming from a stream before it hits the bay. They test their creations and think about ways to improve them.[16]

Inching closer to STEM, students also benefit from data analytic strategies as they collect and analyze evidence in engineering and science projects. As an example, elementary students were observing the hatching and growth of hundreds of silkworm larvae.[17] They closely observed and identified the larvae's related structures *and* their related functions, such as of their mouthparts. The teacher guided students to collect data, including the larvae's length over days, and asked small groups to invent data *displays* that would help the class understand their growth. One group created a chart that illustrated the clumps and holes in this data set. This generated a science question: Why were there so few larvae at each end, especially at the end with the longest larvae, and why were there a lot of holes in that section? Children *conjectured* that this might be due to the timing of the hatching. They remembered that although most of the larvae emerged around the same time, a small number hatched early. These larvae might have gotten a good head start and thus more of the food. The students used the *shape of the data* to investigate the scientific properties of the silkworm larvae.[18]

Moving to full-fledged STEM, computational thinking practices such as looping, conditionals, and debugging can be used to explore science, engineering, and math concepts.[19] Writing code to direct a robot through a maze involves sequencing, looping and conditionals (e.g., "keep going straight until you touch a wall, then turn"), and debugging ("change this left turn to a right turn").[20]

Although all the above are great STE/STEM projects, one thing is missing: opportunities to *learn* math as opposed to *apply* math. And even though these projects include opportunities to learn science, there is the risk that the sequencing of content and skills may not be coherent enough to maximize children's learning. So we value connected STEM learning experiences and believe that practicing and applying math show its usefulness—valuable goals. In addition, however, each domain includes concepts and practices that need to be developed deeply and systematically.[21]

The Challenges of STEM Integration

Some early childhood scholars and educators claim that elementary-grades curricula and pedagogical approaches should *fully integrate* all aspects of STEM and other domains. They believe every planned or emergent experience should include all valued domains: all four STEM domains, and others such as language, literacy, and art. Not only will interconnections be built, they claim, but teaching multiple domains simultaneously will be efficient.[22]

Even if we did not have concerns about the deep learning that is needed in each discipline, the history (including evaluations) of completely integrated educational efforts raises concerns about their exclusive use. For example, reviews of research in preschool

*These units will be available online for free. To learn more, visit go.aft.org/5t6.

and later grades reveal that there is little evidence that fully integrated curricula are superior to traditional structures and that there are challenges in implementing such curricula.[23]

Why *might* this be so? One possibility is that fully integrated activities place excessive demands on students' (and our own—so many topics!) limited cognitive processes.[24] That is, introducing multiple new concepts and principles simultaneously increases the probability that students will struggle or fail to learn them.[25]

Another possibility is that some aspect of the content may not be challenging enough—amounting to an opportunity to practice something already known, but not to learn something new. We saw this in USMES,[26] an acronym for Unified Science and Mathematics for Elementary Schools (informally renamed Unified Science and Mathematics and English for Schools due to the large amount of language and literacy included). Several professors and graduate students at the University of Buffalo worked collaboratively with local fifth-grade classrooms on implementing USMES units. Integration was strong; however, math was usually limited to adding and subtracting whole numbers. Application of math arguably has value: students see the *need* for the subject. However, these experiences taught them nothing new in math. With USMES, the needs of the projects took precedence over the needs of the subject. Students should have been learning topics such as fractions, ratios, and proportions; advanced measurement; and geometry instead of practicing basic arithmetic.

Here's an early childhood example. Planting seeds in spring is good for learning science in pre-K or kindergarten, but counting the few seeds that germinated for each student is a superficial connection[27] that will likely not serve students' needs in math.[28] Counting or better extensions into arithmetic ("How many germinated for the class?") or data ("What was 'usual' for our class?") may be useful practice but are not likely to be at the "cutting edge" of children's math development.

Based on our experience and research, integration can be beneficial but should be planned carefully. A distinct focus on the nature of math is essential, mainly because more than STE, math content and practices may need more explication to support children's understanding and learning.[29] Also, math has an anxiety problem; without developing competence and a productive disposition in math in the early grades, students are unlikely to enter STEM fields.

We agree with Gina Picha, an elementary instructional coach in a Texas public school district, who wrote that "Educators can successfully integrate math with other core subjects, but I wonder why we are focused almost entirely on integration. Integrating mathematics isn't an easy thing to do well. Often times it is math that is put in the passenger seat to lightly serve another subject, project, or task."[30] Again, integration of math in STEM projects is valuable and a valuable contribution to children's confidence and enjoyment of math. However, children also need targeted, high-quality experiences that focus on the cutting edge of their mathematics development.

Creating Our Interdisciplinary Approach

These concerns and our belief that each domain requires unique teaching and learning strategies led us to create an *interdisciplinary approach*.[31] Here, rich connections are made between domains, but each retains its core conceptual, procedural, and epistemological structures. That is, two or more domains are always—and *only*—integrated when that combination is both consistent and complementary with those structures for *each* domain.

Mathematical development is central not only to STEM but also to **overall school success**.

The ideal situation is when the STEM project requires and supports math learning that is meaningful to the children's development. Through such projects, students gain exposure to math skills in an appropriate sequence, and scientific inquiry promotes a deep understanding of concepts and processes. For example, STEM projects may require collecting and representing data at just the right level for students' development of these competencies.

In less-than-ideal situations, sometimes adjustments can be made. For example, suppose the project only uses math the children already know. In that case, teachers can emphasize the usefulness of math *and* teach other math topics outside the project. On the other hand, if a problem or context calls for mathematical concepts or tools that are not yet accessible to students, it may not be the most productive context to explore (or to develop) mathematical understandings and practices within. Another issue to consider is what approach will be most supportive of students' learning. Often, a big disciplinary idea is better introduced alone before it is integrated with another concept or principle within or across disciplines.[32] Instead of jumping right into a STEM activity, teachers might repeatedly foreground the desired math content, temporarily backgrounding other STEM content, and then bring them together. Thus, when connections *are* drawn between math and science, they are genuine and detailed, with their impact undiluted by less fruitful attempts at integration.

To illustrate the potential of this approach, consider an interdisciplinary curriculum for science/engineering, math, literacy, and social-emotional learning called Connect4Learning (C4L) that we have developed along with several other colleagues.[33] The "4" in C4L refers to the four domains we emphasize and to the fact that most children in pre-K, our target setting, are four years old. And, of course, we use the homophone ("four"/"for") to emphasize that we connect the domains *for* learning. That is, we support teachers and children to make connections within and among the domains to support the learning and development of the whole child. We believe it is possible to provide high-quality learning experiences for young children across *all* critical domains—not only in the language and literacy and social-emotional domains—and that the fundamental academic domains of STEM provide rich content on which to build these learning experiences. We integrate them whenever it is advantageous to *each of the domains*, but we do not force integration. We integrate them *if and only if* such integration represents a happy alignment in which the cognitive activity serves children's development in two or more core domains.

One strategy begins with math, for which we have derived research-based developmental sequences of core concepts and core process skills.[34] Through extensive work with young children in real classrooms, we have determined the levels, or patterns, of mathematical thinking and learning most children progress through and how each topic can be sequenced to support another.[35] We call these sequences *learning trajectories*,* and we used them as the basis for C4L, adding on fruitful connections to science. Led by co-author of science Kimberly Brenneman (a program officer for early mathematics at the Heising-Simons Foundation), we found that the science investigations could often be sequenced to maximize opportunities for integration, allowing these units to influence the placement and order of the relatively independent (e.g., geometry vs. number) math learning trajectories.[36]

We integrate STEM domains **if and only if** such integration serves children's development.

The other domains were similarly designed. For example, think-pair-share and collaborative investigations, which promote positive social interactions and executive functions, teach content from other domains. Specific teaching of social and emotional ideas and competencies was designed by co-author Mary Louise Hemmeter (a professor of special education at Vanderbilt University). Literacy competencies were structured into all STEM activities, informed by the broader language and literacy learning trajectories created by co-author Nell Duke (executive director of Stand for Children's Center for Early Literacy Success).

Inappropriate integration was avoided. Let's return to the example of teaching the garden unit in the spring. We agreed that counting the number of seeds each child germinated did not fit our mathematical learning trajectories. The science topic determined the sequence, and therefore we included activities requiring arithmetic operations and geometric shape composition. For example, students make a collage of flowers by composing shapes to make compound geometric figures (consistent with development verified in research).[37] Further, this new math topic is first foregrounded in activities focusing on shapes, their attributes, and how they can be composed.

As another example from a recent project, this one emphasizing structure and function, a class engineered a toy: a ball-and-scoop throw and catch game.[38] To emphasize the STEM ideas,

*Our learning trajectories, along with a wide array of related resources, are available for free at LearningTrajectories.org.

the teacher had a puppet tell the students that he was stuck; his ball wouldn't go into the milk jug scoop. The students told him the hole was too small for the ball. They suggested solutions, including cutting off the whole bottom of the jug or widening the hole at the top of the jug. They used mathematical reasoning (comparing the sizes of a hole and the ball that's supposed to go in it) to determine what is possible physically (science) as they worked iteratively to improve the design of the toy (engineering and technology). They also developed collaboration and language competences as well as literacy skills as they and the teacher cooperatively wrote their own how-to text with the materials and steps required in case another class wants to reproduce the game (literacy).[39]

Another example† involved building ramps.[40] Investigating the science concepts of force and motion, students soon wished to engineer the ramps to maximize their effect: sending an assortment of objects (including balls, toy cars, and plastic dinosaurs) down the ramp and across the floor as quickly and as far as possible. What level of the length measurement learning trajectory had students attained, and thus, what would be the *next* level that would maximize their learning?

Our learning trajectory for measuring length has 12 levels, ranging from Length Senser: Foundations, in which babies as young as six months make simple, intuitive comparisons of length, to Abstract Length Measurer, in which students in grades 4 to 6 meaningfully measure length, compute with lengths in various contexts, and grasp derived units such as miles per hour. Among preschoolers, the most relevant levels are two through six. Level two is the Length Quantity Recognizer, in which children learn what length is (often age 3), and level three is the Length Direct Comparer, in which they physically align two objects to compare lengths. In level six, the End-to-End Length Measurer, students learn to place multiple "units" (e.g., blocks or inch cubes) along the object to be measured and count these individual units to report the length. Children at this level often insist that the linear space *must* be filled by the units (although they may initially leave small gaps between them), but they do not insist that the units must be equal in size! Their goal is simply to fill the space and count to determine the length.

In one classroom, teachers determined that most students could compare lengths directly and were ready to learn End-to-End-level ideas and skills.[41] Therefore, the teachers ensured that students' ramps were oriented differently, prompting them to measure to compare the factors. Teachers also provided enough physical units (e.g., blocks of the same length to place on the floor) that children could develop the End-to-End Length Measurer level of thinking and acting. However, they also saw that several students were soon ready for level eight, Length Unit Relater and Repeater, so they challenged these students by providing them with only a few physical units—and of different sizes. Students collected data on the distances that balls traveled and related them to the science and engineering variables (smoothness of ramp, height of ramp, nascent concepts of slope, and so on), testing and revising their designs and their ideas.

Conclusions and Implications

Integrating domains is a valuable way to promote both meaningful and efficient learning. However, fully integrated approaches to early and elementary education, in which all experiences are guided to include all domains, are unwise. We have described an alternative, *interdisciplinary* approach as one in which rich connections are made between domains but each discipline retains its core conceptual, procedural, and epistemological structures.

Based on our research and classroom experiences, we suggest the following guidelines.[42]

- Maintain high expectations for what children can do in each domain and across domains.
- Use research-supported practices: specific techniques inside and outside of STEM, such as providing practice with subitizing and interactive writing, can be embedded within and contribute to the unit project's purpose.
- Incorporate investigations and explorations, including in math.[43] Educational activities that emphasize exploration and design are often ripe with opportunities for integration.[44]
- Establish a real-world purpose for children's STEM projects. Activities should be realistic or focused on authentic, real-world problems parallel to problems addressed by scientists, engineers, or applied mathematicians.[45]
- Focus on the shared concepts (especially the "big ideas" of a domain), processes, and practices across the STEM domains and make them explicit.
- Consider the role of each domain in the project: it may be easier to see where science and math come in, but be sure to consider technology and engineering as well as literacy, music, and the arts.
- Take an interdisciplinary approach. Look for all possible connections between domains but avoid forcing integration. Ensure that students are learning appropriate content—challenging but achievable. When you do integrate, make the integration explicit and respect what's unique about each discipline, especially how it determines the truth. □

For the endnotes, see aft.org/ae/spring2023/clements_sarama.

†To learn more about this project, the STEM Innovation for Inclusion in Early Education Center, visit stemie.fpg.unc.edu, where you'll find a wide array of free resources and activities for educators and families.