Math, Science, and Technology in the Early Grades

Douglas H. Clements and Julie Sarama

Summary

Do young children naturally develop the foundations of science, technology, engineering, and math (STEM)? And if so, should we build on these foundations by using STEM curricula in preschools? In this article, Douglas Clements and Julie Sarama argue that the answer to both these questions is yes.

First, the authors show that young children possess a sophisticated informal knowledge of math, and that they frequently ask scientific questions, such as *why* questions. Preschoolers' free play involves substantial amounts of foundational math as they explore patterns, shapes, and spatial relations; compare magnitudes; and count objects.

Moreover, preschool and kindergarten children's knowledge of and interest in math and science predicts later success in STEM. And not only in STEM: the authors show that early math knowledge also predicts later reading achievement—even better than early literacy skills do. Thus mathematical thinking, Clements and Sarama say, may be cognitively foundational. That is, the thinking and reasoning inherent in math may contribute broadly to cognitive development.

Is teaching STEM subjects to preschool children effective? The authors review several successful programs. They emphasize that STEM learning for young children must encompass more than facts or simple skills; rather, the classroom should be infused with interesting, appropriate opportunities to engage in math and science. And instruction should follow research-based learning trajectories that include three components: a goal, a developmental progression, and instructional activities.

Clements and Sarama also discuss barriers to STEM teaching in preschool, such as the cultural belief in the United States that math achievement largely depends on native aptitude or ability, and inadequate professional development for teachers.

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The authors wish to express their appreciation to the issue editors and all the contributors to this issue of *Future of Children* for their suggestions for improving this article, and to Camille Driver for her proofreading. The research reported here was supported in part by the Institute of Education Sciences, US Department of Education, through Grant R305A080200 and also R305K05157 and R305A110188 to the Marsico Institute for Early Learning and Literacy, University of Denver. The opinions expressed are those of the authors and don't represent the views of the US Department of Education.

Elida Laski of Boston College reviewed and critiqued a draft of this article.

Other articles in this issue make a strong case that early education is important. The issue we address here is whether early education should include substantial science, technology, engineering, and mathematics (STEM) content—which some educators view, often from ideological perspectives, as appropriate only for older students. To examine this question, we review research on the appropriateness, benefits, and effectiveness of various programs. Our findings are often surprising.

Many adults, including some researchers, believe that "open-ended free play" is good for preschoolers and kindergartners, but "lessons" are not. They don't believe that the youngest children should be taught specific subjects, especially math, science, and technology. They may grudgingly accept math in the primary grades, but they believe that literacy is more important, more motivating, and more appropriate for children. In this article we show that research doesn't support such thinking.

We begin by asking whether young children naturally develop the foundations of STEM. If so, should adults build on these foundations intentionally, for example by using STEM curricula in preschools? Will children enjoy such interactions and learning? Do curricula and intentional teaching produce substantial gains in STEM competencies? What teaching approaches are most effective through the primary grades? Does teaching STEM have other positive effects, such as supporting high-quality play and building executive function and language? If so, what kind of professional development will help teachers engage children in STEM from preschool through third grade? (Note that because more research has focused on mathematics than on the other STEM subjects, our examples tend to favor math.)

Young Children's Surprising Competence in STEM

Especially when they're given opportunities to learn, young children possess a surprisingly broad, complex, and sophisticated informal knowledge of math.[1] For example, they can invent solutions to arithmetic problems by using a variety of strategies. When asked what 75 added to 25 would be, a first-grader told us, "That's like three quarters and one more quarter—so four quarters, a dollar… 100!" Young children also are remarkably successful with geometry tasks that go beyond what older students are usually asked to complete. A kindergartner in one of our studies was making rectangles by inputting a length and a width into a computer program called Logo. He entered 50 and 50, and said, "It's a square! Sure, all sides the same—it's a *square* rectangle."

Young children possess a broad, complex, and sophisticated informal knowledge of math.

Another surprise is how early these competencies develop in all STEM subjects. Even before they begin school, young children possess foundational science and engineering concepts, at least at an implicit level.[2] For example, they ask whether cow babies come from eggs, they observe that people's eyes are different colors (and generate explanations for that), and they frequently ask questions that begin with "why." Entering kindergartners possess knowledge of the natural world, including some understanding of things like cause and effect; the differences between animate and inanimate objects; the ways that people's beliefs, goals, and desires affect their behavior; and substances and their properties. This knowledge includes concepts related to physics, biology, psychology, and chemistry—though admittedly, their intuitions aren't always based on scientific theories, or on any theory at all.

Even infants show sensitivity to principles that adults would classify as physics, measurement, and other science topics. For example, infants as young as three or four months have an intuition that objects need support to keep them from falling. In the first year of life, infants understand that inanimate objects can't move themselves and need to be propelled into action. In one experiment, five- to seven-month-olds watched a film that showed a hand approaching a doll, picking it up, and moving away with it. After seeing this repeatedly, the infants lost interest (called *habituation*). They remained uninterested even when the direction or pace of the movement changed. But when the film changed again to show both the hand and doll moving simultaneously and separately, without the hand touching the doll, the infants showed renewed interest by staring intently. Thus they're sensitive to the fact that the lack of contact between the hand and doll violates the causal principles of physics.

Similarly, children show surprising competencies in mathematics that either are innate or develop in the first years of life. Consider a study in which five-month-old children were repeatedly shown four groups of two dots on a computer screen. Once they were habituated to seeing those groups, they looked longer when shown two groups of four dots—they perceived the difference and were more interested. Other studies have demonstrated that nine-month-olds can distinguish sets of 10 from sets of 15, and that toddlers can use geometric information about the shape of their environment to find objects. Toddlers also show early competence in arithmetic, noticing when a small collection of things increases or decreases by one item. By 24 months, many children have learned number words and begun to count. If young children naturally think and learn about STEM content, then enhancing that learning clearly isn't an imposition.

Young Children's Interest in STEM

In a similar vein, the scientific questions children ask, such as *why* questions, show that science is natural and motivating for young children, as are engineering and technology. Perhaps more surprisingly, this is also true for mathematics, regarding both what children can accomplish and what they're interested in. For instance, preschoolers' free play involves substantial amounts of foundational math. Regardless of their income level and gender, preschoolers explore patterns, shapes, and spatial relations; compare magnitudes; and count objects. As an example, Kyoung-Hye Seo and Herb Ginsburg of Columbia University watched a child putting away blocks by placing each one in a box that contained only other blocks of the same size and shape.[3] They saw three girls draw pictures of their families and discuss the number and ages of their siblings. It's not surprising, then, that high-quality education can help children build on these nascent tendencies. Unfortunately, when such education doesn't begin in preschool and continue through the early years, this potential may be unrealized, leaving children trapped in a trajectory of failure.

The Value of Early Math and Science

Preschool and kindergarten children's knowledge of and interest in math and science predicts later success in STEM.[4] For example, early math knowledge strongly predicts later math achievement, even after controlling for differences in other academic skills, attention, and personal and family characteristics.[5] This surprising result comes not from a single study, but from a meta-analysis that combined six studies, each involving large databases that had followed the same children over time. Essentially, math seems to be a fundamental component of thinking.

Measuring Early Competency in Math and Science

Our methods for measuring early math and science knowledge are important, not only for researchers but also for teachers who wish to discover what their children know and how they can teach them better.[6] Whether we use quick screeners or long diagnostic tests, most assessments should cover skills, facts, concepts, and problem-solving strategies. In math, verbal (rote) counting is a simple skill, whereas problem-solving might be tested by showing children two groups of chips and asking them to count to determine which group has more chips. Posing an arithmetic word problem is another approach.

Assessments should also be age appropriate. Multiple-choice group tests may not be adequate. For teachers, a positive approach to assessing children's strengths and needs should include curriculum-embedded assessment (observing and taking notes during small group instruction), documenting children's talk, and individual interviews. These strategies are more likely to illuminate children's background knowledge and emerging ideas, giving teachers the insight they need. The richer the instructional environment, the broader the range of evidence for assessing learning. Careful assessment is especially important for children with special needs or disabilities.

Teaching Math and Science in the Early Grades

Based on children's foundational competencies and natural interest, learning math and science should be viewed as an appropriate and important educational goal. Teachers need to understand that these subjects encompass more than facts or simple skills.[7] Unfortunately, young children aren't given enough math and science experiences. Teachers spend less time in science learning centers (tables or areas stocked with books and other materials that promote exploration) than in other learning centers, and they rarely offer science-related activities in any context, either planned or spontaneous. Even well-regarded programs for young children tend to have a strong focus on language and social development but a weaker focus on math, and little or no focus on developing children's potential for scientific thinking.

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What's more, the small amount of science that children are taught isn't of high quality.

For example, Head Start children arrive at kindergarten with lower scores in science readiness than in any other area. Many teachers still retain a bias against computer technology, considering it inappropriate in classrooms for young children. With little appreciation for science, math, and technology (not just computer technology, but also the technology and engineering of everyday objects), most teachers are poorly prepared to help young children realize their potential for learning STEM content.

Similarly, most three- and four-year-olds have few or no experiences in mathematics. Teachers often believe they are "doing math" through puzzles, blocks, and songs. But even when such activities do include mathematics, it's not the main focus; instead, the math is embedded in reading or a fine-motor activity. Evidence suggests that such an approach is ineffective.[8]

Too many primary-grade classrooms teach children simple facts and skills that they either already know or can learn relatively quickly, instead of more advanced math concepts. Learning such processes as arithmetic problem-solving and reasoning is arguably more important to their development over time.[9] Even later reading success requires such conceptually oriented science and math instruction.

Certain experiences can ameliorate such problems, however, especially for low-income children and those from minority racial and ethnic groups. But several traditional approaches, such as developmentally appropriate practice, haven't been consistently successful. According to the National Association for the Education of Young Children, *developmentally appropriate practice* involves "meeting young children where they are" and helping them reach goals that are both challenging and achievable. Unfortunately, it hasn't been shown to increase children's learning, perhaps because it's too often restricted to the use of free play only.[10] To combat this lack of learning, we need to infuse the young child's day with interesting, appropriate opportunities to engage in math and science, from preschool through the primary grades.

Learning Better Mathematics

Recently, research-based standards have been developed to describe what should be taught and emphasized when it comes to math. For example, the Common Core State Standards—Mathematics followed research on how children learn as well as the structure of math. Just as important, all math curricula and standards should identify and support a few core ideas rather than many disconnected topics. The best way to achieve academic gains and understanding is to focus on these core concepts coherently, within and across age levels, rather than trying to teach a little of everything at every age.

Moreover, as President Bush's National Mathematics Advisory Panel stated in a comprehensive research review published in 2008, "The curriculum must simultaneously develop conceptual understanding, computational fluency, and problem-solving skills."[11] A study of second-graders shows the benefits of this approach.[12] One group was taught skills along with conceptual understanding, as well as how to flexibly apply multiple strategies. These students scored higher on math tests than did students in a traditional textbook program that focused only on mastering skills. The first group more often selected strategies related to the number properties of the problems, and used strategies more adaptively. Even after months of instruction, the skills-only group didn't apply their skills flexibly. Students who have fluent and adaptive competencies can propose problems, make connections, and then work out solutions in ways that make the connections visible.

Rich learning in mathematics can support existing approaches to early education. For example, children given specific learning activities tend to engage in higher-quality social-dramatic play. That is, children in classrooms that strongly emphasize either literacy or math are more likely to display higher-quality social-dramatic play, while those in classrooms that emphasize *both* have the highest-quality play.[13] By contrast, the lowest gains in learning come from free-play-only classrooms, and even using so-called teachable moments during play is ineffective in these circumstances.[14]

Children also benefit from a related type of play, playing with mathematical ideas. Many researchers consider this the "child as scientist" approach: Children are motivated to explore science concepts while they interact with their environment.[15] As a mathematical example, just after her third birthday, our daughter Abby was playing with three of five identical toy train engines. Passing by, her mother asked, "Where are the other trains?" After her mother was out of sight, Abby was heard speaking to herself. "Oh, I have five. Ummm … [pointing to each engine] you are one, two, three. I'm missing four and five—two are missing! [She played with the trains a few more seconds.] No, I changed my mind … I have one, three, and five. I'm missing two and four. I gotta find them two."

When Abby first figured out how many she was missing, she was using mathematics in her play. But when she decided that she would call the three engines she had one, three, and five, and call the missing engines two and four, she was playing with the notion that assigning numbers to a collection of objects is arbitrary. She was also counting not just objects but words. She counted the words "four and five" to see that two were missing, and then she figured out that counting the renumbered counting words "two" and "four" also yielded the result of "two." She was playing with the idea that counting words themselves can be counted.

Learning Mathematics Better

If developmentally appropriate practice classrooms don't support math learning, how do we ensure that a new approach remains appropriate to children's development?[16] The answer lies in seeing that learning progresses along research-based trajectories. A learning trajectory has three components: a goal, a developmental progression, and instructional activities.[17] To attain a certain competence in a given math topic (the goal), students progress through several levels of thinking (the developmental progression), aided by tasks and experiences (instructional activities) designed to build the mental actions-on-objects that enable thinking at each level.

For example, we might set a goal for young children to become competent counters. The developmental progression describes a typical path that children follow to achieve this. A child might start by learning simple verbal counting, then learn one-to-one correspondence between counting words and objects. The next step is understanding that the final counting word tells *how many*; after that, connecting the final number of the counting process to the cardinal quantity (*how many*) of a set. Finally, the child acquires counting strategies for solving arithmetic problems (up to multidigit problems, for example, 36 + 12: "I counted 36 . . . 46 . . . then 47, 48!"). Although learning trajectories share characteristics with other ways to sequence teaching, they're based on a core of subject-specific knowledge, on cognitive science, and on educational research into how children learn that subject.[18] Most curricula, assessments, and professional development omit critical levels in the learning trajectory for counting and don't recognize these research-based levels in such topics as measurement and geometry.

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Teachers who know how to use and connect the three components of a learning trajectory—content, levels of thinking, and activities that are fine-tuned for their children's level of thinking—are more effective professionals.[19] Without such knowledge, teachers often give young children tasks that are either too easy or too hard, and they don't recognize the mismatch.[20] When teachers understand how levels of thinking progress along these paths, and are able to sequence and individualize activities that are based on these levels, they can build effective math-learning environments. In this way, learning trajectories make it easier to provide appropriate and effective teaching for all children. Substantial work on standards, curricula, and professional development has been based on the concept of learning trajectories in one form or another.[21]

Developing Mathematically Rich Curricula

Through our own program, Building Blocks, we illustrate how a curriculum can be based entirely on learning trajectories and use the kinds of assessment we discussed earlier. From 1998 to the present, we developed and evaluated Building Blocks according to a comprehensive research framework. Our basic approach was to find the mathematics in children's everyday activities and develop math from there. Building Blocks helps children bring math into activities ranging from art and stories to puzzles and games.

We connected every aspect—including text, software, and professional development—to an explicit core of learning trajectories for each math topic. Multiple evaluations have documented that our approach has strong positive effects on children's achievement, even when the curriculum was implemented at a large scale. (One study covered an entire school district, using a scale-up model called TRIAD—short for technology-enhanced, research-based instruction, assessment, and professional development.)[22]

Most groups of children who experienced this curriculum (for example, girls and boys, or children of different income levels) demonstrated equal learning gains, with one notable exception. Although African American children in the control group showed smaller gains than their peers in the same group, African American children in the treatment group showed larger gains than their peers, thus narrowing the initial achievement gap. By providing learning trajectories that help teachers see what children can achieve and how they can be assisted to progress to higher levels, the TRIAD/Building Blocks intervention may be particularly effective in overcoming the negative effects that result from the low expectations some educators hold for African American children when it comes to math learning.[23]

An evaluation of Boston's prekindergarten program offers more evidence of Building Blocks' effectiveness.[24] This study used a different design and evaluated a literacy curriculum combined with Building Blocks. Children in the program scored higher on math, literacy, and language skills than other children, raising a child at the 50th percentile to the 69th to 73rd percentile. Furthermore, the children in the program scored significantly higher in multiple executive-function skills, such as attention-shifting, working memory, inhibitory control, and emotion recognition. (See the article in this issue by Cybele Raver and Clancy Blair for an examination of executive function in young children.) The program narrowed the school readiness gap in early math between poor and non-poor children and eliminated the gap between Latino and white children.

Changing teachers' perceptions of all children's abilities to be strong learners and thinkers about math topics may have substantial benefits. But the above results should be tempered by initial findings from a large evaluation of Building Blocks in New York City. In that study, gains seen at the beginning of prekindergarten were no longer statistically significant when prekindergarten ended. Researchers are still analyzing several other anomalies, including the large amount of math taught in the control classrooms, the lack of high-quality instructional strategies (such as promoting dialogue and formative assessment) in intervention classrooms, and the finding that effects appeared to be greater for children who entered prekindergarten with strong receptive language skills. The evaluation is continuing into the children's kindergarten year.

Other preschool math curricula have shown positive results in high-quality evaluations, including Big Math for Little Kids and the Pre-K Mathematics Curriculum. Table 1 summarizes the main studies. We know of only one direct comparison of Building Blocks with another math curriculum. In that case, Building Blocks outperformed the other curriculum, Pre-K Mathematics, when all other factors were kept the same—that is, the amount of coverage, new materials, and professional development. Beyond this, there is little to tell us which curriculum would be a better choice for any particular context. All successful interventions appear to depend on raising the quality and quantity of specific mathematics teaching strategies. This has implications for policy and practice, as it suggests that although adopting a curriculum is an important step, other factors, such as professional development and coaching, are also critical.

Do positive effects last? Three types of long-term impact are important: sustainability, persistence, and diffusion. *Sustainability* is the continued and accurate use of an innovation such as a curriculum. *Persistence* means that the effects of an intervention on individual children's learning trajectories continue to be felt. *Diffusion* is the process by which an innovation spreads among the

Table 1: Evaluations of Early Mathematics Programs

Program/ Curriculum	Content	Age/ Grade	No. of Children	Design	Results
Building Blocks	Math	Pre-K	276	Random assignment to one of three groups: Building Blocks, Pre-K Mathematics Curriculum, or control	Building Blocks: large effect compared to control; medium effect compared to Pre-K Mathematics Curriculum
TRIAD/ Building Blocks	Math, Language	Pre-K	1,305	Random assignment of schools to one of three groups: TRIAD with follow-through (TRIAD–FT), TRIAD with no follow-through (TRIAD–NFT), and control	Large effect on math; small to medium effect on four of six language subtests
TRIAD follow-through (to Building Blocks)	Math	K	1,218	Random assignment to same three groups as in TRIAD/Building Blocks evaluation	Both TRIAD groups had a medium effect compared to control and were similar to each other.
TRIAD follow-through (to Building Blocks)	Math	1	1,079	Random assignment to same three groups as in TRIAD/Building Blocks evaluation	TRIAD–FT had a medium effect and TRIAD–NFT a small effect compared to control; FT had a small effect compared to NFT.
Building Blocks + OWL	Math Literacy, Executive Function, Emotions	Pre-K	2,018	Comparison of children just above and just below the age cutoff	Medium effect on language, literacy, numeracy, and mathematics skills; small effect on executive function and measure of emotion recognition
Big Math for Little Kids (BMLK)	Math	Pre-K and K	762	Randomly assigned child-care centers	Medium effect
Pre-K Mathematics Curriculum + Building Blocks (software)	Math	Pre-K	276	Classrooms randomly assigned to intervention or control	Moderate effect

Note: Many of these studies included control groups that used a variety of early childhood curricula, most often Creative Curriculum, but also Opening the World of Living, Where Bright Futures Begin, and curricula developed by districts and teachers. Thus we may be confident that business-as-usual curricula don't effectively develop children's potential for learning math.

Sources: Douglas H. Clements and Julie Sarama, "Experimental Evaluation of the Effects of a Research-Based Preschool Mathematics Curriculum," *American Educational Research Journal* 45 (2008): 443–94; Douglas H. Clements et al., "Mathematics Learned by Young Children in an Intervention Based on Learning Trajectories: A Large-Scale Cluster Randomized Trial," *Journal for Research in Mathematics Education* 42 (2011): 127–66; Julie Sarama et al., "The Impacts of an Early Mathematics Curriculum on Emerging Literacy and Language," *Early Childhood Research Quarterly* 27 (2012): 489–502; Julie Sarama et al., "Longitudinal Evaluation of a Scale-up Model for Teaching Mathematics with Trajectories and Technologies," *Journal of Research on Educational Effectiveness* 5 (2012): 105–35; Christina Weiland and Hirokazu Yoshikawa, "Impacts of a Prekindergarten Program on Children's Mathematics, Language, Literacy, Executive Function, and Emotional Skills," *Child Development* 84 (2013): 2112–30; Ashley Lewis Presser et al., "Big Math for Little Kids: The Effectiveness of a Preschool and Kindergarten Mathematics Curriculum," *Early Education and Development* 26 (2015): 399–426; Alice Klein et al., "Effects of a Pre-Kindergarten Mathematics Intervention: A Randomized Experiment," *Journal of Research on Educational Effectiveness* 1 (2008): 155–78; Preschool Curriculum Evaluation Research Consortium, *Effects of Preschool Curriculum Programs on School Readiness* (Washington, DC: Government Printing Office, 2008).

members of a social system—for example, wider dissemination of a curriculum.

Sustainability of implementation is especially important, given the importance of high-quality teaching for any curriculum and the short life of many reforms. Logically, we might expect to see decreasing fidelity after the external support and professional development provided by the intervention teachers have ceased. In the TRIAD/Building Blocks study, however, we saw the opposite: Teachers demonstrated increasing levels of fidelity years after support ended. It would appear that when teachers saw children gaining competence in math, they increased their efforts to carry out all of the intervention's components.

Persistence of effects may be a more important and complex issue than sustainability. Gains made in high-quality prekindergarten interventions often fade in the following few years. Policy makers have tried to promote persistence through alignment (for example, making connections between curricula and assessments within each grade) and continuity (making similar connections across grade levels). We have hints but little empirical evidence that lack of alignment and continuity is at least partially responsible for the fadeout of early gains. We also see some evidence that professional development can support curricular continuity that produces better induction experiences for new teachers, shared goals and instructional strategies, and increased student performance.

The TRIAD project promoted continuity between prekindergarten and the primary grades, testing the hypothesis that gains would appear to fade without follow-through in the primary school years. That is, if children transition into a kindergarten curriculum that assumes little or no competence in math and thus emphasizes low-level skills, children who had a strong prekindergarten math experience would not continue their learning, whereas others might catch up. In the TRIAD evaluation, the effects from prekindergarten persisted when follow-through interventions took place in kindergarten and first grade; without follow-through, the effects were significantly smaller.

Interventions such as TRIAD are exceptions in US schools. Because the new trajectories are exceptions, many things may weaken their positive effects, such as programs that assume low levels of math knowledge and focus on lower-level skills, or a culture of low expectations for certain groups. Without continued support, children's nascent learning trajectories revert to their original, limited course. On the other hand, perhaps stronger prekindergarten interventions are necessary to counteract early disadvantage in children's school-readiness skills. But that approach may be unrealistic when children attend poor-quality schools, as African-American students are more likely to do. Just as experiencing consecutive years of high-quality teaching can have a cumulative positive effect, the opposite is also true.

Diffusion of the innovation is difficult to assess. However, reports have documented diffusion of the TRIAD/Building Blocks intervention in Boston. And New York City schools are adopting the curriculum and the TRIAD model for all prekindergarten classrooms.

Several successful interventions in the primary grades also apply some version of the learning trajectories idea. First-grade teachers in Japan commonly move along multiple learning trajectories, culminating at the point when children develop an effective base-10 strategy to solve addition problems. For example, children solve 8 + 6 by thinking, "I take 2 from the 6 to make the 8 into 10, then have 4 left, so 10 + 4 = 14." Such interventions explicitly promote conceptual understanding by discussing and developing connections among concepts, facts, procedures, and processes. The interventions don't practice basic facts for mastery until the children develop conceptual foundations and meaningful strategies. They challenge students to solve demanding math problems, helping them learn to think mathematically. Interventions like these may offer effective follow-through after prekindergarten programs, thus minimizing the fadeout effect. And they may be particularly successful if they use formative assessment—that is, continuous monitoring of student learning to guide instruction that's based on the idea of learning trajectories.[25]

Three curricula implemented in first and second grade are among the other approaches to primary-grade math that have also been evaluated. One of these is consistent with the learning trajectories approach (Math Expressions), one is a more conventional textbook series, and the third emphasized procedural skills but did make some connections to concepts. All three outperformed a curriculum that was less structured and put more demands on teachers mathematically and pedagogically.[26]

Learning Better Science and Learning Science Better

Like early math education, early science education should be more than a surface treatment of traditional topics—describing the weather, for instance. Research has identified learning trajectories for key topics in science and engineering, such as physics and biology, and evidence shows that following these pathways is educationally effective. Admittedly, efforts to identify learning progressions and core concepts in science are not as far along as they are in math. We still need to identify a few core ideas and to plan standards, curricula, and teaching around those ideas.[27] But we do have a foundation on which to build.

Developing Scientifically Rich Curricula

As with mathematics, high-quality science education that emphasizes richer and deeper content appears to be effective, although experimental and long-term studies have yet to be conducted for most curricula. Early results suggest that consistent science experiences can increase children's vocabulary. They also promote the use of more complex grammatical structures, such as causal connectives: "It's green *because* I mixed yellow and blue paint." Such experiences may also close a science gender gap in motivation and interest.

Several science curricula encourage children as young as preschoolers to think about and work with science concepts (for example, the change in a plant's height) for many weeks or months. Primary grade teachers also need access to all three components of learning trajectories, especially instructional activities that work when connected to their understanding of students' scientific thinking and learning.[28] And our early elementary educators sorely need more professional development in science. Ideally, that would involve multi-year efforts to focus on both subject-matter content and pedagogy.[29]

Effects on Competencies beyond Math and Science

The time spent by primary-grade teachers on science and social studies instruction has decreased in the past 15 to 20 years, and the long-term negative effects on achievement may be substantial.[30] Math and science vocabulary and concepts are essential for reading comprehension, because early math and science instruction develops language within those subjects.[31] And the benefits may run deeper. In one study, children who experienced the Building Blocks curriculum in prekindergarten outperformed children in a control group on four oral language competencies when they were asked to retell a story: ability to recall key words, use of grammatically complex utterances, willingness to reproduce narratives independently, and inferential reasoning. This revealed transfer both in content and in time. That is, the children learned language skills that had not been directly taught in the math curriculum, and they maintained these skills into their kindergarten year.

Such transfer of learning may explain why early math knowledge not only predicts later mathematics achievement, but also predicts later reading achievement—even better than early literacy skills do. Mathematical thinking may be cognitively foundational.[32] That is, the thinking and reasoning inherent in math may contribute broadly to cognitive development. However, we still need to learn more about *how* STEM education supports later language and literacy learning. Would having interesting, sustained conversations on any topic be just as beneficial? We also know little about how much time should be focused on literacy and STEM topics.

Research also suggests that high-quality implementation of math curricula in preschool can develop self-regulation skills (also called executive function skills).[33] These are the cognitive skills that allow people to control, supervise, or regulate their own thinking and behavior, such as the ability to shift attention or hold things in working memory. In math, consider the following problem: "There were six birds in a tree. Three birds already flew away. How many birds were there from the start?" Children must use the executive function of response inhibition to avoid the tempting (but incorrect) procedure of subtraction, engendered by the phrase "flew away." Instead, they must calculate the sum through addition, counting on, or other strategies. In some experiments, the effects of high-quality math on executive function have been found even when they weren't planned. For example, the combination of the Building Blocks math curriculum and the Opening the World of Learning literacy curriculum produced unplanned but positive, albeit small, statistically significant impacts on executive function.

Another study hypothesized that combining Building Blocks with Tools of the Mind, a curriculum designed to develop executive function through play, would produce better results in executive function and in math than a Building Blocks math curriculum alone would. The study further hypothesized that both the combined curriculum and Building Blocks alone would outperform the control group in math.[34] The results were surprising. The Building Blocks group had higher math scores than either of the other groups. Even more surprising was that the Building Blocks group outperformed the others on two measures of executive function, including one that predicts later math achievement.

These and other studies suggest that high-quality math education may have the dual benefit of teaching an important content area and developing at least some executive function processes.[35] They also suggest that preschool curricula can successfully combine social-emotional learning, literacy, language, science, and math, all the while enhancing rather than competing with play-based approaches.[36] We need research on such efforts to see how they can benefit all domains of development.

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Barriers to Teaching Math and Science

Widespread negative dispositions and beliefs about learning and teaching mathematics and about preservice training and professional development in STEM constitute substantial barriers to high-quality teaching.

Negative Dispositions and Beliefs

One deeply embedded cultural belief in the United States is that math achievement largely depends on native aptitude or ability. In contrast, people in other countries, such as Japan, believe that achievement comes from effort. Research shows that the US belief hurts teachers and students and, furthermore, that it just isn't true. Students who believe—or are helped to understand—that they can learn if they work diligently will perform better throughout their school careers than students who believe that a person either gets it or doesn't. That view often leads to failure and what we call "learned helplessness." Similarly, students who have mastery-oriented goals (that is, students who try to learn and see that the point of school is to develop knowledge and skills) achieve more than students whose goals are directed toward high grades or outperforming others.

Early-childhood teachers often hold negative dispositions and beliefs about math and science, including dislike, trepidation, fear, and a doubt in their own efficacy. In one study, the strongest predictor of mathematics learning among preschoolers was their teachers' belief that math education was appropriate for that age group.

Children also need more positive beliefs and attitudes about STEM. As early as the primary grades, math anxiety hurts children's achievement in math. Primary-grade students who score high on working memory but also have math anxiety tend to perform more poorly in math, because their working memory capacity is co-opted by anxiety. Primary graders who feel panicky about math have increased activity in brain regions associated with fear, and decreased activity in brain regions involved in problem-solving. If we can identify and treat math anxieties early, we may be able to keep children with high potential from avoiding math courses.

Fortunately, most very young students have positive feelings about math; they're motivated to explore numbers and shapes.

But it takes just a couple of years in typical schools before they begin to believe that only some people have the ability to do math. We believe that students who experience math as a sense-making activity, rather than a series of timed tests, will build positive feelings about math throughout their school careers. Similarly, we can change teachers' negative dispositions and beliefs through high-quality preservice and professional development, a subject to which we now turn.

Professional Development Is Inadequate

Even though children are eager to learn, many early childhood teachers aren't eager or prepared to engage children in rich experiences in domains other than literacy. Historically, teachers of young children haven't been prepared to teach subject-specific knowledge to young children. In-service professional development also tends not to emphasize math and science, despite learning standards and increased curricular attention to these subjects. Of 50 state-funded preschool programs, 41 require at least 15 hours of in-service training per year. But content decisions are made locally, and STEM is usually ignored. Professional development must help teachers explore content and pedagogy in depth. It must also confront the distaste for math that is widespread among teachers of young children—and directly related to girls' achievement in their classes.

Research on professional development for math teachers offers some guidance. For example, certification alone doesn't reliably predict high-quality teaching—probably because certification programs vary widely and too many are of low quality. On the other hand, direct measures of teachers' knowledge of math and math pedagogy do predict the quality of their teaching.[37]

In general, research suggests that effective professional development in early STEM is continuous, intentional, reflective, goal-oriented, and focused on content knowledge and children's thinking; it's grounded in particular curriculum materials, and situated in the classroom. But all training needn't occur in the classroom. While research-based curricula can help teachers learn to teach STEM, teachers need to understand all three components of a learning trajectory—goals (the STEM content), developmental progressions, and instructional activities. This requirement appears to place too heavy a burden on curricula alone, even on curricula designed to help teachers learn.

Teachers also need off-site, intensive training that focuses on these three components and the connections among them—though such training must be connected to classroom practice. Then they need time to try out the new strategies in their classrooms, supported by coaches who give them feedback. The success of Building Blocks, TRIAD, and other projects can largely be attributed to such professional development organized around learning trajectories. These projects included far more extensive and intensive professional development than the usual one-shot workshop, ranging from five to 14 full days.

Technology and Engineering

Young children are motivated by such simple engineering tasks as building with blocks, and by interacting with technology.[38] Unfortunately, few researchers have examined engineering among young children. Block-building has been widely studied, so we know that preschoolers' competence at this activity predicts the number of math courses they take and their grades in high school. Furthermore, developmental progressions for block-building are well established.

Various computer technologies can improve how and what children learn about STEM, and about other subjects. However, the T in STEM refers to *learning about* technology rather than *using* technology, and learning how to apply it to solve problems. Therefore, we will only briefly describe computer-assisted instruction, and then we'll move on to more active technologies.

Computer-Assisted Instruction (CAI)

CAI means structured software that instructs students or lets them practice. Experiments show that practice software can help young students develop competence in such skills as counting and sorting, and in addition facts.[39] CAI can also teach at-risk first graders the add-1 rule (adding 1 is the same as "counting one more") by way of pattern detection.[40] The software asks, "What number comes after 3 when we count?" and then immediately follows by posing a related addition question, "3 + 1 = ?". The software also discourages children from overgeneralizing by giving counterexamples to the add-1 rule. Research reviews of rigorous studies show that when such applications are well designed and implemented, they have a positive impact on children's math performance—raising a child from the 50th to the 61st to 68th percentile across different studies.[41]

Games may also be effective. Second-graders who averaged one hour of interaction with a technology game over a two-week period responded correctly to twice as many items on an addition facts speed test as students in a control group.[42]

Computer Manipulatives

Other approaches that have also received support address STEM more directly, as they teach children to use tools for discovery and for problem-solving. A recent review of 66 studies found that the use of computer manipulatives raised a child from the 50th to the 64th percentile.[43] This positive effect may come from the following seven advantages of technology-based manipulatives and activities: (1) They bring mathematical ideas and processes to conscious awareness; (2) they encourage and facilitate complete, precise explanations; (3) they support mental actions on objects; (4) they can change the nature of the manipulative (for example, computer shapes can be precisely cut apart or scaled, unlike wooden or plastic shapes); (5) they symbolize mathematical concepts; (6) they link the concrete and the symbolic with feedback; and (7) they record and replay students' actions.

Syntheses of Approaches

Technologies that use a combination of these teaching strategies and tools can help children follow learning trajectories. Manipulative-based, dynamic models can help children develop foundational understandings. Connecting multiple representations (such as manipulatives, spoken words, symbols, and actions) helps to build understanding and to connect children's own concrete and symbolic mental representations, all while they're learning to use the tools to solve problems. For example, the Building Blocks software employs a series of technological activities that incorporate manipulatives and board games to progressively develop children's competence in counting. This leads to counting-based addition and subtraction strategies. If children make several consecutive mistakes, they receive brief hints and then tutorials. A management system moves the children along a research-based learning trajectory, using formative assessment to ensure that each child is learning new concepts and skills through tasks that are challenging but achievable. Building Blocks software was one of the strongest mediators of children's learning, but it's still unclear exactly how the software contributed to learning. Significantly, a separate study showed that the Building Blocks software was effective even when used alone, raising a child from the 50th to the 67th percentile.[44]

Logo and Coding: Computer Science and Engineering

Many types of software let children build STEM objects virtually. The oldest and most-studied software that teaches all four STEM subjects for early childhood is called Logo. In Logo's computer coding, children begin by directing an onscreen robot or turtle to draw geometric shapes. Many children can draw shapes with pencil and paper, but drawing shapes using Logo commands requires them to analyze the visual aspects of the shape and the movements needed to draw it. Writing a sequence of Logo commands to draw a shape encourages children to think precisely about that process.

After working with the robot or turtle, students show greater explicit awareness of the properties of shapes and the meaning of measurements. An evaluation of a Logo-based geometry curriculum across grades K–6 revealed that Logo students scored statistically higher than control-group students on a general geometry achievement test, making about twice the gains of children in comparison groups (raising a child from the 50th to the 82nd percentile).[45]

Finally, computer coding shouldn't be considered work on virtual worlds only. In robotics environments, for example, children are engineers. They create LEGO structures that have lights, sensors, motors, gears, and pulleys, and they control their structures through computer code. The few studies that have examined LEGO–Logo suggest that such experiences can positively affect children's math and science achievement as well as their higher-order thinking skills. If they start as young as kindergarten, both boys and girls benefit from work with robots, and few differences appear between them. Recently, researchers have described how very young children at different developmental levels approach programming a robot, which suggests that this may be a promising approach for future engineering experiences.

Conclusions

Children from preschool through the primary grades are interested in learning about STEM and can think about these subjects in ways that are surprisingly broad and deep. Not only does math competency predict later school success, but all areas of STEM contribute to other developmental goals, such as language and executive function. Children whose teachers use research-based approaches demonstrate higher levels of STEM achievement and thinking. Learning trajectories can support children's learning, and can also aid in assessment and curriculum development. Children whose teachers use research-based learning trajectories demonstrate higher levels of mathematical reasoning.

Current research in learning trajectories points the way toward math learning that is more effective and efficient—but also creative and enjoyable—through culturally relevant and developmentally appropriate curricula and assessment. However, we still have much to learn about teaching certain topics in STEM and about the characteristics of curriculum development and professional development that will let children realize their full potential in these critical subjects.

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