STEM Smart Brief

STEM Smart: Lessons Learned From Successful Schools

Improving STEM Curriculum and Instruction: Engaging Students and Raising Standards

THE PROBLEM

The glazed eyes, the hands propping up heads, the giggling in the back of the room: these are the all-too-common signs of disengaged students in STEM classes across the country. Algebra, geometry, trigonometry, biology, chemistry, physics—some of the most important topics in U.S. education—are among the toughest to teach well.

The problem is not simply academic; it is economic. If the U.S. fails to increase the number of students mastering STEM content and preparing for STEM careers, the nation will fall farther and farther behind in the global economy—and that affects us all.

Striking Statistics: The Need for STEM-Capable Workers[1]

* The current demand for STEM-capable workers surpasses the supply of applicants who have trained for those careers.
* Some 16 of the 20 occupations with the largest projected growth in the next decade are STEM related.
* Only four of the STEM-related occupations with the largest projected growth require an advanced degree. The rest also require specialized training, but typically an associate's degree or bachelor's degree is sufficient.

Recent research funded by the National Science Foundation to identify best practices in STEM education shows that students in all types of schools, regardless of size or specialty, *can and do* engage in high-quality science, mathematics, and engineering. But the extent to which students actually *do* learn these subjects is a different issue. And the consensus is bleak: "Effective STEM instruction is the exception in the vast majority of schools…. It is typically facilitated by extraordinary teachers who overcome a variety of challenges that stand between vision and reality."[2] For effective K–12 STEM instruction to become the norm, schools and districts must be transformed.

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THE RESEARCH & PROMISING PRACTICES

Many factors affect student learning, including school culture to teacher ability to parent support. U.S. schools are trying new ways to improve math and science education by focusing on a variety of these areas. But at the core of the efforts are the age-old questions of what to teach and how to teach it—curriculum and instruction. To many, the answer is clear: the curriculum must be focused, rigorous, and coherent; the instruction must be provided by teachers with deep content knowledge and the pedagogical ability to make that content accessible to students.

Curriculum and Standards

Studies of international K–12 curricula and standards highlight a major difference between the United States and other countries. Most of the world's developed nations have for years created uniform national curriculum standards, which detail the content to be covered by teachers at each grade level, to ensure quality instruction. Such standards serve as a national roadmap for curriculum materials, teacher preparation, and training.

A number of studies suggest that a focused and aligned K–12 curriculum facilitates learning in STEM subjects. Because these subjects typically are based on hierarchical structures that rely on prior learning to determine future understanding, the absence of focused and aligned curricula may prevent mastery. Research also shows a clear link between what students are expected to learn and actual math learning: greater achievement is associated with covering fewer topics in greater depth.

The United States, with its preference for local control, historically left this critical work of creating standards up to individual states. The different directions each state took led to huge variation in the focus, coherence, and rigor of standards. Compared with the highest-performing nations on the international TIMSS exam, U.S. state STEM curriculum standards have problems in all three areas: they are less focused, with too many topics covered in each grade; less rigorous, with students studying more basic topics; and less coherent, with an often illogical progression from topic to topic.[3]

Even when curriculum standards are clearly articulated, rigorous, and coherent, the highlighted material is not always taught sufficiently. There is wildly different content coverage within a single grade level, even within the same school, especially in terms of the sequence of topics and the total time spent studying specific areas. These inequalities affect entire school systems, not just the traditionally disadvantaged.

Many educators are optimistic that important work to solve these problems has begun with the adoption of the national *Common Core State Standards* (CCSS) in Mathematics and the development of the National Research Council's Framework for K–12 Science Education. The goal is that the national guidelines will help states to develop math and science curricula that focus on the most important topics, are logically sequenced over time, and engender a deeper understanding. Adopted by 44 states and the District of Columbia, the CCSS, which include math and English, is a big break with past practice and is expected to have a positive impact. The adoption of the Common Core will be a challenge for teachers, but an important one for them to master.

Engaging Instruction

The National Research Council's Framework for K–12 Science Education makes student engagement the top priority. Educators increasingly recognize the challenge of ensuring that instruction not only covers the most important math and science content, but does so in a way that can entice even bored or distracted students.

Research in STEM learning over the past two decades has a lot to say about what makes for effective, engaging STEM education. Among the key factors: it capitalizes on students' early interests and experiences, identifies and builds on what they know, and provides opportunities to engage in the practices of science and mathematics to sustain their interest. In other words, throughout their schooling, students should learn to investigate questions about the world that they come across in daily life, in much the same way that scientists and mathematicians do.

Also showing promise in STEM learning at the college level is interactive engagement, particularly group problem solving. For example, teachers can pose a question and encourage students to work together in groups to come up with a consensus response. This allows for on-the-spot reasoning and discussion, and, moreover, allows students to test their own understanding.[4] Peer instruction, which requires students to apply concepts learned in class and to teach other students, has also shown promise for the same reasons outlined above, and because it engages every student in the class. Studies of peer instruction have been found to increase student learning, particularly in concept mastery.[5]

Encourage students to be scientists and mathematicians

The possibilities for getting students involved in interesting STEM experiences are endless and can be adapted to different levels of difficulty for different grades. Here are just a few ideas: compare heights of young students with and without shoes to investigate the ins, outs, and hows of measurement; explore and categorize plant and animal species on the school's grounds to learn about biodiversity; design, build, and race air-canister-powered wooden cars in different shapes to explore aerodynamics. Each of these activities has the potential to be a valuable STEM learning experience if the teacher structures and facilitates the lesson, allowing for students to come up with their own questions, data, and conclusions—much like scientists and mathematicians.

The National Research Council report *Taking Science to School* describes science as a social phenomenon in which a community of peers pursues shared objectives and abides by shared conventions that shape their work: building and refining theories and models, collecting and analyzing data from observations and experiments; constructing and critiquing arguments; and using specialized ways of talking, writing, and representing phenomena.[6] Students of any age can do these things at their own developmental levels, with appropriate modeling and supports from their teachers.

Successful teachers provide frequent opportunities for students to engage in logical arguments as they learn to build and refine explanations for their observations, allowing students to design and conduct empirical investigations, connect the investigations to core knowledge, and work from a curriculum linked to meaningful problems. .[7]

Start early

Contrary to conventional wisdom, it's never too early to promote student interest in science and mathematics. Recent research has recommended that every effort should be made to start as soon as children enter elementary school. Studies have identified the elementary years as the period when students form their interests in STEM identities and careers—much earlier than many people probably believe to be the case. This is particularly important for science, which gets short shrift in many elementary schools.[8]

Teach often

Indeed, research has recommended elevating science to the same importance as reading and math in early schooling, devoting adequate instructional time and resources. While time spent on mathematics instruction generally has increased in recent years, there has been a corresponding decrease in time spent on science instruction. It is one of the unintended consequences of the No Child Left Behind emphasis on reading and math in elementary school. In a national survey, 28 percent of districts reported decreasing time for science instruction—down an average of 75 minutes per week.[9] Compared with spending 323 minutes per week on math and 503 minutes per week on English, districts spend only about 178 minutes per week on science instruction. This must improve.

Example: The Mystery Box (Grades K–2)

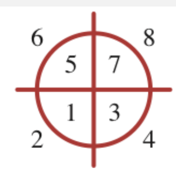
The following describes an early elementary school science activity that teaches much more than might be apparent. In this Mystery Box investigation[10], the teacher asks her young students to gather around her and a toaster-oven-sized wooden chest with a heavy lock. She points to two identical sets of six spoons and forks made of three different materials—wood, plastic, and metal. She puts one set of the spoons and forks in a bag and then takes out a single utensil and puts it in the Mystery Box. The mystery? The students have to figure out which utensil is inside. With a dramatic flair, the teacher says the words she always uses to start the Mystery Box game: "If you ask me a question about what's inside the Mystery Box, I will tell you the truth."

One girl immediately asks, "Is it the plastic spoon?" The teacher commends her for her excellent question and explains why it is a good one—because it provided helpful information—that it is not the plastic spoon inside the box. She takes away the plastic spoon from the row in front of the students.

The teacher then chooses a Popsicle stick with a student's name on it to make sure that each child has an equal chance of getting a turn and asks a boy what question he wants to ask. The boy, having recently moved to the U.S. from Central America, has some trouble with the language, but with help asks, "Is it a fork?" The teacher says, "That's another good question, because it's not a fork"—and she takes away all three forks, leaving only two possibilities, a wooden spoon or a metal spoon, in the row in front of the students. The teacher suddenly exclaims that she just noticed something interesting—that the first question got rid of only one item but the second question eliminated three and she asks them why. One girl makes a concrete observation, and then another explains "It's like we got three answers with one question." Soon the children figure out that the hidden object is the wooden spoon. The teacher says, "Ta dah… congratulations," and the kids all break into applause.

This activity surely seems a long way from advanced physics, but it illustrates many of the important features of an effective lesson and how to get the youngest students interested in science, including using reasoning abilities to draw inferences about something they can't see. The children are thinking about how to ask questions and how to learn from other people's questions; they are learning that different kinds of questions can produce different amounts of information; and—perhaps most important—they are learning that getting the right answer is not the only thing that matters in a scientific investigation. Indeed, negative evidence can be very useful.

Example: What's My Number? (Grades 1–3)



A similar game in mathematics is especially effective if the teacher is silent during the game. The teacher draws the diagram (on right) and gives the rules: "I'm thinking of one of these numbers. You are detectives trying to figure out what number I'm thinking of. You may ask any questions, but I never say a word. I just nod yes (nod to demonstrate) or no (demonstrate). Or I shrug my shoulders (demonstrate) if I don't know how to answer. Oh, and I'll count your questions on my fingers, like this (teacher shows 1, 2, 3, 4 on one hand). You may ask four questions. Then, if you say my number, you win. Otherwise I win! Ready? I'm thinking of a number." Several children raise their hands. Students start by asking questions like "Is it 4?" "Is it 7?" Partly because the teacher is dead silent, not even repeating the questions, children are riveted! And, of course, to win, they must listen to each other and watch for the answer and remember both the questions and the answers. With "pure-guess" questions, the kids don't win very often. Eventually a child asks a question like "Is it a big number?" The teacher shrugs, and some other child says "is it one of those top numbers, like 5, 6, 7, or 8?" More often, the first fancy question will be "Is your number in the circle?" For questions like these, a "no" answer is just as good as a "yes." And then the children are winning all the time![11]

Example: Molecules in Motion (Grade 7)

In this example, a seventh-grade class explores a new concept in an engaging manner that actually encourages deeper student exploration of the concept. In this case study[12], the teacher starts a unit on air, called "Molecules in Motion," and begins with a demonstration of air pressure using everyday objects that produce surprising outcomes designed to elicit student thinking.

The teacher fills a 10-gallon aquarium with water and food coloring and provides several different sized drinking glasses. Making the comparison to doing the dishes, the teacher fully submerges one glass, and then lifts it above the surface of the water, showing that water stayed in the glass above the tank. Students then ask to do it again with a larger glass, and they try different sized glasses along with a graduated cylinder. They observe the phenomenon several times before the teacher poses the question "What's making the water stay in the glass?" As anticipated by the teacher, many students come up with suction as an explanation.

The teacher acknowledges this misconception and does one more demonstration before directing students to work in stations on four other experiments, similar to the class demonstration, which will allow students to make additional observations of the phenomenon and draw their own conclusions through the class discussion. All are designed to prove to students that air takes up space. In the end, students generated their own list of the properties of air they observed, which the teacher compared with the scientifically accepted list. However, students arrived at these findings themselves, rather than memorizing them, which changes their conceptual thinking.

The importance of research projects for students is highlighted in several NRC reports and workshops. These take many forms, but a few examples illustrate their capacity to engage students and expand their thinking.

RECOMMENDATIONS

There are many ways to increase student interest and motivation in science, mathematics, and engineering, including:

- Relate science to students' daily lives
- Employ hands-on tasks and group activities
- Use authentic learning activities
- Incorporate novelty and student decision-making into classroom lessons
- Ensure that STEM curricula focus on the most important topics in each discipline

Yes, this is a challenging endeavor. Educators must develop a toolbox of approaches that is large enough to stimulate the interest of many students and flexible enough to meet the needs of a wide variety of young people, who have a wide variety of motivations.

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[1] T.A. Lacey & Wright, B. (2009). Occupational employment projections to 2018. *Monthly Labor Review, 132* (11), 82-123. Available at http://www.bls.gov/opub/mlr/2009/11/art5full.pdf

[2] National Research Council, Committee on Highly Successful Schools or Programs for K–12 STEM Education. (2011). *Successful K–12 STEM education: identifying effective approaches in science, technology, engineering, and mathematics*. Washington, DC: The National Academies Press.

[3] Schmidt, W. H. (2011). *STEM reform: Which way to go?* Paper presented at the National Research Council's Workshop on Successful STEM Education in K–12 Schools, Washington, DC, May 10-12, 2011.

[4] Wieman, C. & Perkins, K. (2005). Transforming physics education. *Physics Today, 58*(11). Retrieved from http://70.40.207.144/sdsu_per/articles/Transforming%20Physics%20Education%20-%20Physics%20Today%20November%202005.pdf

[5] Crouch, C. H. & Mazur, E. (2001). Peer instruction: Ten years of experience and results. *American Journal of Physics, 69*(9), 970–977.

[6] National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K–8.* Washington, DC: The National Academies Press.

[7] National Research Council. (2011). *Successful STEM education: A workshop summary*. Alexandra Beatty, Rapporteur. Committee on Highly Successful Schools or Programs for K–12 STEM Education, Board on Science Education and Board on Testing and Assessment. Washington, DC: The National Academies Press.

[8] McMurrer, J. (2008). *Instructional time in elementary schools: A closer look at changes for specific subjects.* Washington, DC: Center on Education Policy. Retrieved from http://www.cep-dc.org/displayDocument.cfm?DocumentID=309.

[9] McMurrer, J. (2008). *Instructional time in elementary schools: A closer look at changes for specific subjects.* Washington, DC: Center on Education Policy. Retrieved from http://www.cep-dc.org/displayDocument.cfm?DocumentID=309.

[10] This is based on a program, the Investigators Club, developed and researched with funding from the Spencer Foundation. It was described in National Research Council (2008). *Ready, set, science!*: *Putting research to work in K-8 science classrooms*, Washington, DC: The National Academies Press.

[11] Education Development Center, Inc. (2008). *Think Math*. Retrieved from http://thinkmath.edc.org/index.php/What%27s_my_number%3F

[12] National Research Council (2008). *Ready, set, science!*: *Putting research to work in K–8 science classrooms.* Washington, DC: The National Academies Press.

Community for Advancing Discovery Research in Education

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