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Applying New Research to Improve Science Education

Insights from several fields on how people learn to become experts can help us to dramatically enhance the effectiveness of science, technology, engineering, and mathematics education.

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Science, technology, engineering, and mathematics (STEM) education is critical to the U.S. future because of its relevance to the economy and the need for a citizenry able to make wise decisions on issues faced by modern society. Calls for improvement have become increasingly widespread and desperate, and there have been countless national, local, and private programs aimed at improving STEM education, but there continues to be little discernible change in either student achievement or student interest in STEM. Articles and letters in the spring and summer 2012 editions of *Issues* extensively discussed STEM education issues. Largely absent from these discussions, however, is attention to learning.

This is unfortunate because there is an extensive body of recent research on how learning is accomplished, with clear implications for what constitutes effective STEM teaching and how that differs from typical current teaching at the K-12 and college levels. Failure to understand this learning- focused perspective is also a root cause of the failures of many reform efforts. Furthermore, the incentive systems in higher education, in part driven by government programs, act to prevent the adoption of these research-based ideas in teaching and teacher training.

A new approach

The current approach to STEM education is built on the assumption that students come to school with different brains and that education is the process of immersing these brains in knowledge, facts, and procedures, which those brains then absorb to varying degrees. The extent of absorption is largely determined by the inherent talent and interest of the brain. Thus, those with STEM “talent” will succeed, usually easily, whereas the others have no hope. Research advances in cognitive psychology, brain physiology, and classroom practices are painting a very different picture of how learning works.

We are learning that complex expertise is a matter not of filling up an existing brain with knowledge, but of brain development. This development comes about as the result of intensive practice of the cognitive processes that define the specific expertise, and

effective teaching can greatly reduce the impact of initial differences among the learners.

This research has established important underlying causes and principles and important specific results, but it is far from complete. More research is needed on how to accomplish the desired learning most effectively over the full range of STEM skills and potential learners in our classrooms, as well as how to best train teachers.

What is learning STEM?

The appropriate STEM educational goal should be to maximize the extent to which the learners develop expertise in the relevant subject, where expertise is defined by what scientists and engineers do. This is not to say that every learner should become a scientist or engineer, or that they could become one by taking any one class, but rather that the value of the educational experiences should be measured by their effectiveness at changing the thinking of the learner to be more like that of an expert when solving problems and making decisions relevant to the discipline. As discussed in the National Research Council study *Taking Science to School*, modern research has shown that children have the capability to begin this process and learn complex reasoning at much earlier ages than previously thought, at least from the beginning of their formal schooling. Naturally, it is necessary and desirable for younger children to learn less specialized expertise encompassing a broader range of disciplines than would be the case for older learners.

Expertise has been extensively studied across a variety of disciplines. Experts in any given discipline have large amounts of knowledge and particular discipline-specific ways in which they organize and apply that knowledge. Experts also have the capability to monitor their own thinking when solving problems in their discipline, testing their understanding and the suitability of different solution approaches, and making corrections as appropriate. There are a number of more specific components of expertise that apply across the STEM disciplines. These include the use of:

- Discipline- and topic-specific mental models involving relevant cause and effect relationships that are used to make predictions about behavior and solve problems.
- Sophisticated criteria for deciding which of these models do or don't apply in a given situation, and processes for regularly testing the appropriateness of the model being used.
- Complex pattern-recognition systems for distinguishing between relevant and irrelevant information.
- Specialized representations.
- Criteria for selecting the likely optimum solution method to a given problem.

- Self-checking and sense making, including the use of discipline-specific criteria for checking the suitability of a solution method and a result.
- Procedures and knowledge, some discipline-specific and some not, that have become so automatic with practice that they can be used without requiring conscious mental processing. This frees up cognitive resources for other tasks.

Many of these components involve making decisions in the presence of limited information—a vital but often educationally neglected aspect of expertise. All of these components are embedded in the knowledge and practices of the discipline, but that knowledge is linked with the process and context, which are essential elements for knowledge to be useful. Similarly, measuring the learning of most elements of this expertise is inherently discipline-specific.

How is learning achieved?

Researchers are also making great progress in determining how expertise is acquired, with the basic conclusion being that those cognitive processes that are explicitly and strenuously practiced are those that are learned. The learning of complex expertise is thus quite analogous to muscle development. In response to the extended strenuous use of a muscle, it grows and strengthens. In a similar way, the brain changes and develops in response to its strenuous extended use. Advances in brain science have now made it possible to observe some of these changes.

Specific elements, collectively called “deliberate practice,” have been identified as key to acquiring expertise across many different areas of human endeavor. This involves the learner solving a set of tasks or problems that are challenging but doable and that involve explicitly practicing the appropriate expert thinking and performance. The tasks must be sufficiently difficult to require intense effort by the learner if progress is to be made, and hence must be adjusted to the current state of expertise of the learner. Deliberate practice also includes internal reflection by the learner and feedback from the teacher/coach, during which the achievement of the learner is compared with a standard, and there is an analysis of how to make further progress. The level of expert-like performance has been shown to be closely linked to the duration of deliberate practice. Thousands of hours of deliberate practice are typically required to reach an elite level of performance.

This research has a number of important implications for STEM education. First, it means that learning is inherently difficult, so that motivation plays a large role. To succeed, the learner must be convinced of the value of the goal and believe that hard work, not innate talent, is critical. Second, activities that do not demand substantial focus and effort provide little educational value. Listening passively to a lecture, doing many easy, repetitive tasks, or practicing irrelevant skills produce little learning. Third, although there are distinct differences among learners, for the great majority the amount of time spent in deliberate practice transcends any other variables in determining learning outcomes.

Implications for teaching

From the learning perspective, effective teaching is that which maximizes the learner's engagement in cognitive processes that are necessary to develop expertise. As such, the characteristics of an effective teacher are very analogous to those of a good athletic coach: designing effective practice activities that break down and collectively embody all the essential component skills, motivating the learner to work hard on them, and providing effective feedback.

The effective STEM teacher must:

- Understand expert thinking and design suitable practice tasks.
- Target student thinking and learning needs. Such tasks must be appropriate to the level of the learner and be effective at building on learners' current thinking to move them to higher expertise. The teacher must be aware of and connect with the prior thinking of the learner as well as have an understanding of the cognitive difficulties posed by the material.
- Motivate the student to put in the extensive effort that is required for learning. This involves generating a sense of self-efficacy and ownership of the learning; making the subject interesting, relevant, and inspiring; developing a sense of identity in the learner as a STEM expert; and other factors that affect motivation. How to do this in practice is dependent on the subject matter and the characteristics of the learner—their prior experience, level of mastery, and individual and sociocultural values.
- Provide effective feedback that is timely and directly addresses the student's thinking. This requires the teacher to recognize the student's thought processes, be aware of the typical cognitive challenges with the material, and prepare particular questions, tasks, and examples to help the learner overcome those challenges. Research has shown several effective means of providing feedback, including short, focused lectures if the student has been carefully prepared to learn from that lecture.
- Understand how learning works, and use that to guide all of their activities. In addition to the research on learning expertise, this includes other well-established principles regarding how the human brain processes and remembers information that are relevant to education, such as the limitations of the brain's short-term memory and what processes enhance long-term retention.

Although many of these instructional activities are easier to do one on one, there are a variety of pedagogical techniques and simple technologies that extend the capabilities of the teacher to provide these elements of instruction to many students at once in a classroom, often by productively using student-student interactions. Examples of approaches that have demonstrated their effectiveness can be found in recommended reading articles by Michelle Smith and by Louis Deslauriers et al.

Effective STEM teaching is a specific learned expertise that includes, and goes well beyond, STEM subject expertise. Developing such teaching expertise should be the focus of STEM teacher training. Teachers must have a deep mastery of the content so they know what expert thinking is, but they also must have “pedagogical content knowledge.” This is an understanding of how students learn the particular content and the challenges and opportunities for facilitation of learning at a topic-specific level.

This view of STEM teaching as optimizing the development of expertise provides clearer and more detailed guidance than what is currently available from the classroom research on effective teaching. Most of the classroom research on effective teaching looks at K-12 classrooms and attempts to link student progress on standardized tests with various teacher credentials, traits, or training. Although there has been progress, it is limited because of the challenges of carrying out educational research of this type. There are a large number of uncontrolled variables in the K-12 school environment that affect student learning, the standardized tests are often of questionable validity for measuring learning, teacher credentials and training are at best tenuous measures of their content mastery and pedagogical content mastery, and the general level of these masteries is low in the K-12 teacher population. The level of mastery is particularly low in elementary- and middle-school teachers. All of these factors conspire to make the signals small and easily masked by other variables.

At the college level, the number of uncontrolled variables is much smaller, and as reviewed in the NRC report *Discipline-Based Education Research*, it is much clearer that those teachers who practice pedagogy that supports deliberate practice by the students show substantially greater learning gains than are achieved with traditional lectures. For example, the learning of concepts for all students is improved, with typical increases of 50 to 100%, and the dropout and failure rates are roughly halved.

Shortcomings of the current system

Typical K-16 STEM teaching contrasts starkly with what I have just described as effective teaching. At the K-12 level, although there are notable exceptions, the typical teacher starts out with a very weak idea of what it means to think like a scientist or engineer. Very few K-12 teachers, including many who were STEM majors, acquire sufficient domain expertise in their preparation. Hence, the typical teacher begins with very little capability to properly design the requisite learning tasks. Furthermore, their lack of content mastery, combined with a lack of pedagogical content knowledge, prevents them from properly evaluating and guiding the students’ thinking. Much of the time, students in class are listening passively or practicing procedures that neither have the desired cognitive elements nor require the level of strenuousness that are important for learning.

Teachers at both the K-12 and undergraduate levels also have limited knowledge of the learning process and what is known about how the mind functions, resulting in common educational practices that are clearly counter to what research shows is optimum, both

for processing and learning information in the classroom environment and for achieving long-term retention. Another shortcoming of teaching at all levels is the strong tendency to teach “anti-creativity.” Students are taught and tested on solving well-defined artificial problems posed by the teacher, where the goal is to use the specific procedure the teacher intended to produce the intended answer. This requires essentially the opposite cognitive process from STEM creativity, which is primarily recognizing the relevance of previously unappreciated relationships or information to solve a problem in a novel way.

At the undergraduate level, STEM teachers generally have a high degree of subject expertise. Unfortunately, this is not reflected in the cognitive activities of the students in the classroom, which again consist largely of listening, with very little cognitive processing needed or possible. Students do homework and exam problems that primarily involve practicing solution procedures, albeit complex and/or mathematically sophisticated ones. However, the assigned problems almost never explicitly require the sorts of cognitive tasks that are the critical components of expertise described above. Instructors also often suffer from “expert blindness,” failing to recognize and make explicit many mental processes that they have practiced so much that they are automatic.

Another problem at the postsecondary level is the common belief that effective teaching is only a matter of providing information to the learner, with everything else being the responsibility of the learners and/or their innate limitations. It is common to assume that motivation, and even curiosity about a subject, are entirely the responsibility of the student, even when the student does not yet know much about the subject.

Failure of reform efforts

The perspective on learning that I have described also explains the failure of many STEM reform efforts.

Belief in the importance of innate talent or other characteristics. Schools have long focused educational resources on learners that have been identified in some manner as exceptional. Although the research shows that all brains learn expertise in fundamentally the same way, that is not to say that all learners are the same. Many different aspects affect the learning of a particular student. Previous learning experiences and sociocultural background and values obviously play a role. There is a large and contentious literature as to the relative significance of innate ability/talent or the optimum learning style of each individual, with many claims and fads supported by little or questionable research.

Researchers have tried for decades to demonstrate that success is largely determined by some innate traits and that by measuring those traits with IQ tests or other means, one can preselect children who are destined for greatness and then focus educational resources on them. This field of research has been plagued by difficulties with selection

bias and the lack of adequate controls. Although there continues to be some debate, the bulk of the research is now showing that, excepting the lower tail of the distribution consisting of students with pathologies, the predictive value of any such early tests of intellectual capability is very limited. From an educational policy point of view, the most important research result is that any predictive value is small compared to the later effects of the amount and quality of deliberate practice undertaken by the learner. That predictive value is also small compared to the effects of the learners' and teachers' beliefs about learning and the learners' intellectual capabilities. Although early measurements of talent, or IQ, independent of other factors have at best small correlation with later accomplishment, simply labeling someone as talented or not has a much larger correlation. It should be noted that in many schools students who are classified as deficient by tests with very weak predictive value are put into classrooms that provide much less deliberate practice than the norm, whereas the opposite is true for students who are classified as gifted. The subsequent difference in learning outcomes for the two groups provides an apparent validation for what is merely a self-fulfilling prophecy. Given these findings, human capital is clearly maximized by assuming that, except for students with obvious pathologies, every student is capable of great achievement in STEM and should be provided with the educational experiences that will maximize their learning.

The idea that for each individual there is a unique learning style is surprisingly widespread given the lack of supporting evidence for this claim, and in fact significant evidence showing the contrary, as reviewed by Hal Pashler of the University of California at San Diego and others.

Because of the presence of many different factors that influence a student's success in STEM, including the mind's natural tendency to learn, some students do succeed in spite of the many deficiencies in the educational system. Most notably, parents can play a major role in both early cognitive development and STEM interest, which are major contributors to later success. However, optimizing the teaching as I described would allow success for a much larger fraction of the population, as well as allowing those students who are successful in the current system to do even better.

Poor standards and accountability. Standards have had a major role in education reform efforts, but they are very much a double-edged sword. Although good definitions and assessments of the desired learning are essential, bad definitions are very harmful. There are tremendous pitfalls in developing good, widely used standards and assessments. The old concept of learning, combined with expert blindness and individual biases, exerts a constant pressure on standards to devolve into a list of facts covering everyone's areas of interest, with little connection to the essential elements of expertise. The shortcomings in the standards are then reinforced by the large-scale assessment systems, because measuring a student's knowledge of memorized facts and simple procedures is much cheaper and easier than authentic measurements of expertise. So although good standards and good assessment must be at the core of any serious STEM education improvement effort, poor standards and poor

assessments can have very negative consequences. The recent National Academy of Sciences–led effort on new science standards, starting with a carefully thought-out guiding framework, is an excellent start, but this must avoid all the pitfalls as it is carried through to large-scale assessments of student mastery. Finally, good standards and assessments will never by themselves result in substantial improvement in STEM education, because they are only one of several essential components to achieving learning.

Competitions and other informal science programs: Attempting to separate the inspiration from the learning. Motivation in its entirety, including the elements of inspiration, is such fundamental requirement for learning that any approach that separates it from any aspect the learning process is doomed to be ineffective. Unfortunately, a large number of government and private programs that support the many science and engineering competitions and out-of-school programs assume that they are separable. The assumption of such programs is that by inspiring children through competitions or other enrichment experiences, they will then thrive in formal school experiences that provide little motivation or inspiration and still go on to achieve STEM success. Given the questionable assumptions about the learning process that underlie these programs, we should not be surprised that there is little evidence that such programs ultimately succeed, and some limited evidence to the contrary. The past 20 years have seen an explosion in the number of participants in engineering-oriented competitions such as First Robotics and others, while the fraction of the population getting college degrees in engineering has remained constant. A study by Rena Subotnik and colleagues that tracked high-school Westinghouse (now Intel) talent search winners, an extraordinarily elite group already deeply immersed in science, found that a substantial fraction, including nearly half of the women, had switched out of science within a few years, largely because of their experiences in the formal education system. It is not that such enrichment experiences are bad, just that they are inherently limited in their effectiveness. Programs that introduce these motivational elements as an integral part of every aspect of the STEM learning process, particularly in formal schooling, would probably be more effective.

Silver-bullet solutions. A number of prominent scientists, beginning as far back as the Sputnik era, have introduced new curricula based on their understanding of the subject. The implicit assumption of such efforts is that someone with a high level of subject expertise can simply explain to novices how an expert thinks about the subject, and the novices (either students or K-12 teachers) will then embrace and use that way of thinking and be experts themselves. This assumption is strongly contradicted by the research on expertise and learning, and so the failure of such efforts is no surprise.

A number of elements such as school organization, teacher salaries, working conditions, and others have been put forth as the element that, if changed, will fix STEM education. Although some of these may well be a piece of a comprehensive reform, they are not particularly STEM-specific and by themselves will do little to address the basic shortcomings in STEM teaching and learning.

The conceptual flaws of STEM teacher in-service professional development. The federal government spends a few hundred million dollars each year on in-service teacher professional development in STEM, with states and private sources providing additional funding. Suzanne Wilson's review of the effectiveness of such professional development activities finds evidence of little success and identifies structural factors that inhibit effectiveness. From the perspective of learning expertise, it is clear why teacher professional development is fundamentally ineffective and expensive. If these teachers failed to master the STEM content as full-time students in high school and college, it is unrealistic to think they will now achieve that mastery as employees through some intermittent, part-time, usually voluntary activity on top of their primary job.

Why change is hard

First, nearly everyone who has gone to school perceives himself or herself to be an expert on education, resulting in a tendency to seize on solutions that overlook the complexities of the education system and how the brain learns. Second, there are long-neglected structural elements and incentives within the higher education system that actively inhibit the adoption of better teaching methods and the better training of teachers. These deserve special attention.

Improving undergraduate STEM teaching to produce better-educated graduates and better-trained future K-12 teachers is a necessary first step in any serious effort to improve STEM education, but there are several barriers to accomplishing this. First, the tens of billions of dollars of federal research funding going to academic institutions, combined with no accountability for educational outcomes at the levels of the department or the individual faculty member, have shaped the university incentive system to focus almost entirely on research. Thus, STEM departments and individual faculty members, regardless of their personal inclinations, are forced to prioritize their time accordingly, with the adoption of better teaching practices, improved student outcomes, and contributing to the training of future K-12 STEM teachers ranking very low. Second, to the limited extent that there are data, STEM instructional practices appear to be similarly poor across the range of postsecondary institutions. This is probably because the research-intensive universities produce most of the Ph.D.s, who become the faculty at all types of institutions, and so the educational values and standards of the research-intensive universities have become pervasive. Third, with a few exceptions, the individual academic departments retain nearly absolute control over what they teach and how they teach. Deans, provosts, and especially presidents have almost no authority over, or even knowledge of, educational practices in use by the faculty. Any successful effort to change undergraduate STEM teaching must change the incentives and accountability at the level of the academic department and the individual faculty member in the research-intensive universities.

A possible option would be to make a department's eligibility to receive federal STEM research funds contingent on the reporting and publication of undergraduate teaching

practices and student outcomes. A standard reporting format would make it possible to compare the extent to which departments and institutions employ best practices. Prospective students could then make more-informed decisions about which institution and department would provide them with the best education.

Most K-12 teacher preparation programs have a local focus, and they make money for the institutions of which they are a part. There is no accepted professional standard for teacher training, and there is a financial incentive for institutions to accept and graduate as many education majors as possible. This has resulted in low standards, particularly in math and science, with teacher education programs frequently having the lowest math and science requirements of any major at the institution. This also means that they attract students with the greatest antipathy toward math and science. Research by my colleagues has found that elementary education majors have far more novice-like attitudes about physics than do students in any other major at the university. Federal programs to support the training of K-12 STEM teachers provide easily available scholarship money, which reinforces the status quo by ensuring a plentiful supply of students in spite of the programs' low quality. Rewarding institutions that produce graduates with the expertise needed to be highly effective teachers is an essential step in bringing about the massive change that is needed in the preparation of STEM teachers.

Focusing on STEM learning and how it is achieved provides a valuable perspective for understanding the shortcomings of the educational system and how it can be improved. It clarifies why the current system is producing poor results and explains why current and past efforts to improve the situation have had little effect. However, it also offers hope. Improvement is contingent on changes in the incentive system in higher education to bring about the widespread adoption of STEM teaching methods and the training of K-12 teachers that embody what research has shown is important for effective learning. These tasks are admittedly challenging, but the results would be dramatic. The United States would go from being a laggard in STEM education to the world leader.

Recommended reading

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