NATIONAL ACADEMY of EDUCATION

# Science and Mathematics Education

EDUCATION POLICY WHITE PAPER

Not since the launch of the Soviet Sputnik satellite spurred the federal government to begin investing in science and mathematics education through the National Defense Education Act have these two areas of the school curriculum been so high on state and federal policy agendas. Policy makers, business leaders, educators, and the media again worry that future United States expertise in the areas of science, technology, engineering, and mathematics is in jeopardy.[1] Improving public education, particularly in science and mathematics, continues to be viewed as an important national economic and social issue. These concerns have led to the formulation of many local, state, and national education policies that include elements such as targeted scholarships, increased course-taking requirements for graduation, end-of-course exams in high school, investments in labs and equipment, and in some cases, higher pay to attract teachers to these fields.

These efforts are worthy. But, they are not enough. They are scattered and incoherent—even *within* states and school districts—and neglecting this lack of coherence will limit what can be accomplished. Cross-state initiatives, with federal assistance, are needed to increase coherence and build the capacity of schools and districts across the country to provide high quality science and mathematics instruction.

One goal of such initiatives should be to ensure that the United States continues to have sufficient numbers of highly skilled scientists, mathematicians, engineers, health professionals, technicians, and science and mathematics teachers. For that to happen, schools must develop and sustain the interest of students in these disciplines, and business, higher education, and government must create opportunities for them to pursue successful scientific and technical careers. A second and equally important goal must be to equip all Americans with the knowledge and skills they need to be effective citizens and to function in the workplace. Such skills include being able to argue from evidence, solve complex problems, work in teams, and interpret and communicate complex information.[2] Science and mathematics education has a critical role to play here, too.

***Science and Mathematics Education***
***Education Policy White Paper***


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## A Call for Coherent Systems of Teaching and Learning

An instructional system has four major components that any reform effort must encompass: curriculum, assessments, teachers, and supports for teachers and students. To function well, the curriculum should focus on essential concepts and skills that build over time. Assessments should measure the full range of knowledge and skills in the curriculum and help inform instruction as well as monitor performance. Teachers need to understand the content deeply, know effective methods for teaching it, and be able to create a classroom environment conducive to learning. Teachers should also have at their disposal adequate space, materials, equipment, technology, and class time to implement the curriculum. All four components, along with strategies for attracting and retaining competent science and mathematics teachers, must work in concert for science and mathematics education to be effective.

Our focus here is on ways to improve science and mathematics achievement in the United States through systemic and linked changes in all four of these components, along with instructional use of the powerful technologies that now pervade science, mathematics, and engineering. The linking of these components is essential, for it is the only way to make a complex system coherent.

The system needs to be made coherent in several ways. It must be made coherent *vertically*, which means that students' science and mathematics learning should build from year to year. Students should not need to learn the same concepts and skills over and over as they move through the grades. They also should be able to count on having learned prerequisite material when introduced to new content. This requires curricula that are well-articulated through the various administrative levels of the educational system—the classroom, the school, the district, and the state. Teacher preparation should be explicitly linked to these curricula. The system also must be coherent *horizontally*, which means that districts and states need to coordinate their curricula so that—within the limits of America' evolving federal system of education—students moving to a new school or a new state will have a reasonable chance of picking up where they left off without being subjected to lessons on content they already know, or struggling through lessons for which they are unprepared.

With those goals in mind, we recommend a systems-engineering approach to reform. Typically, discrete education reforms in the United States are piloted in a few settings for a short period of time, evaluated, and then abandoned or continued depending on the outcomes and the availability of funds. As an alternative, we recommend starting with curriculum, standards, and assessments that *together* define a common core of science and mathematics knowledge. Curricula, teaching materials (including technology tools), and teacher preparation that are aligned with the common core all should be subjected to an iterative cycle of design, testing, implementation, evaluation, and redesign to achieve the quality and coherence that are needed.

## A Path to Coherence

There is not sufficient evidence on details of what works in teaching science and mathematics to justify quick movement toward a single national curriculum in either subject. There is, however, substantial agreement among scientists, mathematicians, educators, and scholars of learning on the important strands of mathematical and scientific knowledge and skills that students should master in order to be judged proficient.

For science, the National Research Council study *Taking Science to School*[3] concluded that a student who is proficient in science:

- Knows major scientific ideas and can apply them appropriately,
- Can collect and analyze evidence from experiments and observations,
- Understands that science is a way of knowing about the world and can apply this to his or her own thinking, and
- Can argue from evidence, identify ways to test an idea, formulate hypotheses that can be tested, use diagrams to represent ideas and record data, and participate in other scientific practices.

To this list of core science competencies, we add a fifth strand that comes from engineering[4]:

- A student who is proficient in science also understands the designed world and the concepts of engineering and design.

Mathematicians and students of mathematics learning have been working to identify the core strands of their fields since before 1923, the year the final report of the National Committee on Mathematical Requirements was published.[5] The consensus of the National Research Council study, *Adding It Up*,[6] was that a student who is proficient in mathematics has acquired:

- Conceptual understanding of key mathematical ideas, operations, and relations;
- Fluency with mathematical procedures and the ability to use them flexibly, accurately, efficiently, and appropriately;
- Strategic competence (i.e., the ability to formulate, represent, and solve mathematical problems);
- Adaptive reasoning (i.e., the capacity to think logically and reflectively and to explain and justify one's thinking); and
- A productive disposition that sees mathematics as sensible, useful, and worthwhile, and that recognizes that diligence and effort will lead to results.

The five strands in science and mathematics are not identical, but they are all based in research on learning and play a similar role in broadening the definition of what is to be learned (we will refer to them jointly here as "the strands"). According to the groups that articulated these consensus documents on the goals of science and mathematics instruction, all of the strands should be interwoven in an instructional *system* throughout curricula used for teaching and learning.[7]

Although widely agreed upon, these visions of coherent science and mathematics instruction are not now reflected in educational practice—especially in science. State-developed standards in science vary widely in content and quality. Textbook publishers, understandably, want to create a textbook series for a national market, so they often try to cover everything called for in a given grade by any state. The textbooks that result rarely help students and teachers understand what distinguishes science as a discipline. Nor do they offer a strong and carefully designed progression of core ideas and concepts. The National Research Council report *Taking Science to School* says that the pre-high school science curriculum "rarely builds cumulatively and in developmentally informed ways."[8] Curricula and texts present materials cafeteria-style, leaving it up to teachers to choose which concepts to emphasize and which ones to pass over. The experience for students is a series of disconnected lessons or activities that "cover(s) a limited slice of content."[9]

The situation in mathematics is somewhat better. The National Research Council report *Adding It Up* noted that "current state standards and curriculum frameworks vary considerably in their specificity, difficulty, and character."[10] Promising national mathematics frameworks have since been created.[11] There is generally agreement on what should be taught in each grade, and more time is being spent on mathematics in the school curriculum.[12] But, implementation has been poor. Still, compared with those of high-performing nations such as Japan, Korea, Portugal, Singapore, and Sweden, United States standards and curricular materials for mathematics continue to sprawl over many topics within and across the grades. The final report of the National Mathematics Advisory Panel concluded that "the mathematics curriculum in grades Pre-K–8 should be streamlined and should emphasize a well-defined set of the most critical topics in the early grades."[13] And in particular, a national initiative should be undertaken to improve the teaching and learning of mathematics for all children ages 3 to 6 years.[14]

Curricula and course sequences for high school science and mathematics present separate but related problems. At the high school level, the needs of students who intend to pursue careers in science and mathematics are different from the needs of those who do not. Yet, typical high school course sequences are designed as if all students will continue their studies in science and mathematics into college. Challenging and rigorous pathways through high school designed to serve everyone are needed, but as yet those pathways have had insufficient study for us to recommend the precise form they should take. Thus, we make different curriculum development recommendations for pre-kindergarten to 8th grade than we do for high school.

Reforms of the scale needed will likely take decades to come to full fruition and will require both patience and unrelenting effort and focus.[15] But the fundamental tasks that must be taken on are clear. They include rethinking the curriculum and standards, and providing a small set of coherent teaching options that meet the needs of different state constituencies. The nation must begin now to formulate a path and take initial steps toward a coherent system of educational opportunities in science and mathematics for all students.

**RECOMMENDATION 1: The federal government should strengthen the pre-kindergarten through 8th grade science and mathematics curriculum by supporting the National Science Foundation to fund the development of several curricula that focus on core concepts and skills, thereby preparing all students to succeed in high school. The materials should include related curriculum support materials, professional development tools, and assessments.**

The nation is now in a position to build on emerging agreements about what should be taught and learned to support the development and testing of several internally coherent curriculum options in both science and mathematics. By *curriculum*, we do not mean just a series of topics that students will learn. Rather, we use the term to mean a developmentally sequenced set of learning activities, together with formative assessments and associated teacher training strategies. If the goal is for algebra to be introduced in the 8th grade, for example, then the sequence of learning activities starting in the earliest grades must be developed with that in mind. Similarly, if a goal is for students to understand the inquiry process of science and the principles that have been established through that process, then the curriculum should be so designed, with explicit attention to both scientific reasoning and core concepts. In addition to a curriculum sequence and instructional materials that build from year to year, teachers need to have available to them appropriate technology, laboratories, equipment, and materials.

We recommend that multiple development projects be funded by the federal government to build this foundation for effective teaching and learning of science and mathematics. The government should fund proposals that seem likely to produce several different approaches, each coherent within itself. The funding agency should establish criteria for awarding grants that provide for horizontal and vertical integration across several states as a part of each project. The development efforts should include teams of experts in the subject matter, content-specific practices of teaching, assessment, cognitive development, project evaluation, and the creation of educational technology, textbooks, and curricula.

Each project should build a consortium of states that agree in advance to align their standards with the consortium's core standards for what students should know and be able to do at each grade level in science and mathematics. The states also should be expected to align their state assessments with those standards, and may agree to use common year-end and formative assessments. To gain federal support, the projects should be asked to demonstrate that they will create curricula that define proficiency in a way that includes all five strands of learning in each subject and that weaves the strands together from the earliest grades.

The curricula should include texts, materials, equipment, and technologies that support investigation and experimentation, problem solving, and argumentation as integral components of the learning process. The materials should, for example, include technology for simulations, data acquisition, and analysis. They should allow for collaborative study as well as for individual learning of specific skills and concepts. Resources to help teachers use the materials and embedded assessments to measure student progress and inform teaching are also critical components.

Research on the effectiveness of the instructional approaches devised by the projects should begin as soon as they are implemented in classrooms. The findings of this research should be used to improve the approaches. The research could lead, for example, to revisions in the pace and sequence of the curricular units, which will require related revisions of state standards to match the realigned benchmarks. We elaborate on the nature of the research needed in Recommendation 6, which calls for the incorporation of engineering design principles into education research.

**RECOMMENDATION 2: High school course sequences and curricula in science and mathematics should be rethought and redesigned.**

The organization of science and mathematics in American high schools has not changed greatly in more than 100 years, even as scientific knowledge, technological advancements, the technical demands of the workplace, and competition in the global economy have greatly increased what high school graduates need to know and be able to do. Students are not served particularly well by these course sequences—whether they plan to seek quantitative or scientific careers or not. High schools must attend to the needs of both kinds of students and better pathways for each must be designed. Although we see much that is not ideal in the current system, the path forward—and thus, our recommendations—are less clear. There is, however, a clear need to improve the scope and the sequence of high school science and mathematics courses and we suggest here some options worth investigating.

Today's course sequences in science and mathematics do not necessarily prepare and motivate a diverse group of students to pursue careers in science and engineering.[16] In particular, research shows that although female students are now taking more advanced physical science and mathematics in high school, those courses are not drawing many of them into the pool of would-be practitioners in these areas.[17] The situation for disadvantaged students, particularly those from under-represented groups, is significantly worse, with few such students enrolling in advanced classes, and fewer yet planning to major in these fields.

Course content and sequences should be reconsidered with a goal of aligning them with the five strands of proficiency for science and mathematics and providing intellectually coherent instructional sequences in each field.

### Science

The most common course sequence in science is Biology followed by Chemistry and Physics. This sequence is "out of order" in scientific terms, however. In biology class, 9th graders are introduced to the complex molecules within cells and the structure of DNA even though they know little about atoms and next to nothing about the chemistry and physics that can help them make sense of these structures and their functions. Furthermore, because of the limited course requirements in most states, standard science course sequence often means in practice that many high school students never study physics at all. Although 21 states require students to take at least five semesters of science to graduate, only four currently require three years of laboratory science (this will increase to eight states by 2012).[18]

To add to the confusion, some schools offer courses with titles such as Earth Science or Astronomy outside the sequence. These courses may contain important content and good teaching strategies, but they further limit the degree of coherence in many students' experience. A course in Integrated Science combines all of the scientific disciplines and attempts to create greater coherence, but in practice is typically taken mainly by students who do not intend to study science formally past high school. In short, the science instruction students receive in high school varies greatly in content and quality, and rarely builds to a coherent understanding of the field.

Efforts have been made to change the standard sequence of biology, chemistry, and physics. But the 10th-grade science test that most states require emphasizes biology and thereby reinforces the existing sequence. Alternatives such as teaching all areas of science every year, or reversing the sequence by putting a physics course first, have been tried but typically without investing in the curriculum and professional development required to realize the potential of such change.

There are several potentially effective ways to reorganize the high school science curriculum. What is important is that each state—or consortium of states—chooses one, using the best evidence available. The choice process should include the active engagement of a group of professionally trained scientists and educators, and build toward a coherent program for all students. A serious investment is needed in the development and implementation of a science sequence of course options that prepare children to be scientifically literate and to become lifelong learners as science and technology continue to advance and become more complex.[19] We recommend that the federal government fund the development and testing of several model high school course sequences, courses, and syllabi along with the associated textbooks, investigation guides, technological tools, and teacher support materials. Models for such work exist,[20] although they may need some broadening of scope. The development teams should include experts in the subject areas, the teaching of science, cognitive development, assessment, curriculum development, educational technology development, and textbook writing, as well as a set of schools or districts willing to be the developmental trial sites.

The sequence should be designed to ensure not only that students learn facts but that they have opportunities to engage in scientific investigations and argumentation. Such participation will help students to develop conceptual understanding, alongside the skills of analyzing and arguing from evidence through which science develops and establishes knowledge.[21] Instructional technologies show promise for supporting conceptual learning, and their use should be built into these curriculum designs.

### Mathematics

Currently, the most common mathematics sequence is Algebra I, Geometry, and then Algebra II; Precalculus follows. Advanced students begin the sequence earlier and may take a year, or even two, of Advanced Placement Calculus in high school. This sequence and the courses involved do not adequately serve those students who do not intend to continue studying mathematics in college. Nearly 30 states require three or more years of mathematics to graduate, but only Texas currently requires students to take the Algebra I-Geometry-Algebra II sequence.[22] We are especially concerned about the proposal—apparently gaining support in many states—that Algebra II be treated as the capstone of a required high school mathematics sequence. The traditional Algebra II course was never intended for all students and thus does not make sense as a requirement for high school graduation. Furthermore, with Algebra II as the capstone course, there is no room for deep treatment of important topics in data analysis, probability, trigonometry, elementary functions, or discrete mathematics.

The very concept of year-long courses, each devoted to a single domain of mathematics, is an anachronism. No other developed country offers separate year-long courses in algebra and geometry. Japanese students, for example, study the contents of a U.S. algebra course and geometry course over three years, starting in the 7th grade. By the 10th grade, they are ready to study advanced algebra.[23] But in the United States, so-called integrated mathematics courses are not widely offered.

Requiring more high school students to take algebra and geometry, when they haven't been well-prepared for success by their program in elementary and middle school, has led to the creation of courses that have the same or similar names but vary widely in content, rigor, and intellectual demand. There are algebra courses that span two years and geometry courses that do not require students to learn proofs. The National Mathematics Advisory Panel[24] recently addressed this problem by articulating a vision for the content of introductory algebra. The Achieve consortium is also making some progress on this challenge.[25]

Data from the Trends in International Mathematics and Science Study (TIMSS) reveal the relative lack of focus, rigor, coherence, and uniformity in curricula in the United States.[26] According to ACT, the testing organization, many students who take and pass three years of high school mathematics must take remedial mathematics, including arithmetic, before they are prepared to take an entry-level college algebra course.

In mathematics, too, the federal government can encourage and support several multi-state consortia to develop a common framework for a new integrated mathematics course sequence from grades 9 through 12. The consortia also should develop associated standards and assessments using a process like that described earlier.

**RECOMMENDATION 3: The federal, state, and district officials responsible for assessment should ensure that assessments in science and mathematics measure higher levels of thinking and reasoning as well as students' content knowledge and skills.**

Assessments should model the kinds of tasks that students should be working on to become proficient. Two potential models for this type of assessment are the 2009 framework for the National Assessment of Educational Progress (NAEP) in science and mathematics[27] and the current Programme for International Student Assessment (PISA) framework.[28] Each is designed to assess a spectrum of knowledge, skills, and the ability to use them in varied contexts. United States science and mathematics assessments need to move in this direction, which will require research, test development, field testing, and refinement to make sure new testing approaches meet appropriate technical standards. Assessment systems should also include classroom assessments that will inform teachers' instruction as well as monitor student progress.[29]

Currently, most of the 50 states contract separately with testing companies to produce assessments aligned with their standards. Test items often can be—and are—used in multiple states, yet each state pays separately for item development. Not only is this inefficient, it also undermines efforts to improve science and mathematics education across states. Shared state standards and assessments should make the process more efficient, allowing resources to be used to develop and to administer forms of testing that include open-ended responses that are currently viewed as too expensive to administer. The federal government should provide incentives for states to work together to improve assessments. Recently, Rhode Island, New Hampshire, and Connecticut agreed on a common science assessment,[30] and 48 states (along with the District of Columbia, Puerto Rico, and the United States Virgin Islands) have agreed to develop a common core of standards for mathematics and reading.[31] This promising approach is now being extended to science.

The assessments suggested in the teacher's edition of textbooks are frequently used by teachers in classrooms to monitor their students' mastery of the material, but little is done in the textbook creation process to ensure that assessment tasks include the most central cognitive processes and relevant applications of each curricular unit. Nor are textbooks built to help teachers identify student misconceptions or to help teachers build on existing conceptions to make progress toward more complete understanding.[32] Attention to these aspects of the texts should become part of the criteria for textbook approval or selection by states and school districts.

**RECOMMENDATION 4: Improve the preparation, professional development, and work conditions (including remuneration) of science and mathematics teachers in order to attract and retain individuals who are competent in teaching these challenging subject matters.**

The curricular incoherence in the United States presents a problem in how to design teacher education programs. For science and mathematics, teacher preparation should be built around the particular curriculum that the teacher will use. Today this is nearly impossible given the many fundamentally different curricula used in schools where the graduates of any teacher education program will teach. The development of several widely-used curricula, and of related assessments, would help solve this problem for districts and states that adopted them.

Teaching science and mathematics successfully is complex work that demands both great knowledge and skill. We are just beginning to understand the specialized nature of the content and pedagogical knowledge that such teaching requires.[33] But we know that teachers need to be able to anticipate and recognize students' common naïve misconceptions and errors and have at their command examples and counterexamples to illuminate core topics. They need to be able to interpret students' responses and questions and use them to frame further instruction. The ability to adapt mid-lesson to students' responses depends on teachers' own fluent understanding of the science and mathematics concepts they are teaching.

Few teacher preparation programs pay special attention to the detailed content knowledge and pedagogical content knowledge[34] specific to teaching science and mathematics. This is especially true for programs that prepare elementary school teachers, and often extends to middle school teachers as well. Teachers need to know the content they will teach. However, taking high-level college science or mathematics courses alone does not necessarily prepare them to teach these subjects well, especially to elementary and middle school students. Teachers also need subject-specific mentoring early in their careers as well as continued options for improving their content knowledge and their knowledge about the challenges of teaching that content.

What is needed to solve this problem is far more coordination between education and disciplinary faculties in universities, and more rigorous programs to ensure that teacher candidates are well-grounded in both the subject matter and the teaching strategies specific to that subject matter. Models for such programs exist (e.g., the Learning Assistant program at the University of Colorado and the parallel courses in subject matter and pedagogy in the University of Georgia's Middle School Science and Mathematics Teacher Education Program[35]). These need to be studied further, improved, and made more widely available.[36] We recommend that the federal government support the design, implementation, evaluation, and revision of such programs by colleges and universities. The National Science Foundation's PhysTec[37] collaboration, which has been supporting such work in physics, provides an example of how such funding can stimulate collaboration between disciplinary and education departments. State governments can help by developing teacher certification policies that reward districts for hiring teachers who have gone through rigorous programs. Also needed are effective continuing professional development opportunities (including those offered only online) available to teachers throughout their careers.

One way to reduce the cost of professional development for elementary school teachers while still increasing the quality of teaching is to deploy specialists in these areas starting in the upper elementary grades. Multiple models have shown some promise,[38] such as having one specialist teacher support multiple teachers, or having a small team of teachers for a group of classrooms at a given grade level divide the work so that each teacher takes specialized responsibility for a limited set of subject areas for all classes in the group of classrooms. These models, and matched plans for teacher preparation and certification, are worth exploring further.

There is a shortage of well-qualified science and mathematics teachers in middle and high schools.[39] To recruit and retain teachers with the required level of science and mathematics skills, teaching must compete as a profession with the other scientifically-oriented professional options that these individuals can pursue.[40] States and school districts should experiment with differential pay scales for teachers of different subject matters. Teachers of mathematics, for example, may need to be paid more than teachers of English or social studies, and teachers of high school chemistry and physics may need to be paid yet more.[41]

Along with teacher pay, working conditions are a key element of the recruitment and retention equation. Among the important working conditions are appropriate equipment to conduct science experiments or demonstrate scientific principles, and time for collegial collaborative work. In addition, there should be a recognizable career path that encourages teachers to join and remain in the profession and to continue to improve their teaching competence. In mathematics, improved teacher competence has been shown to have a greater effect on achievement than a costly reduction in class size.[42]

**RECOMMENDATION 5: In funding curriculum development in science and mathematics, federal agencies should ensure that these efforts include comprehensive technology-based instructional and assessment resources.**

Twenty-five years of research on educational applications of information and communication technologies (ICTs) in science have shown that students can learn important concepts of science, technology, engineering, and mathematics earlier and more deeply when they use ICT models and tools to explore them.[43] Carefully designed simulations and computer models can help students visualize and understand complex concepts about objects and processes. Computer-linked technology for gathering and analyzing data (e.g., probeware that gives instant feedback about the processes being studied during lab experiments) also plays an important role in school laboratory science. Indeed, the growing application of ICTs is associated with higher scores on NAEP.[44] In mathematics, too, well-designed programs that use technology effectively to anticipate student responses and teach specific concepts and skills are producing learning gains.[45] The networking that is integral to modern computers creates important learning opportunities that include collaboration, access to large databases, and distributed data collection—all of which can be incorporated into curricula that address the five science and mathematics strands. ICT can also support improved student assessment, providing regular assessments of students using computer-based materials, and creating the possibility of more affordable performance-based assessments using simulated equipment.

The "digital gap" in education has much less to do with whether ICTs are available than with how those technologies are being used.[46] In fact, the well-designed use of ICT tools appears to be just as valuable in under-resourced urban classrooms—including those with many English–language-learners—as elsewhere.[47] With support from administration and staff, ICT can significantly enhance student learning in urban settings.[48] The National Research Council Committee on Learning Science in Informal Environments recently highlighted the importance of attending to the learning of science by students from diverse cultural and ethnic backgrounds, noting that "much more attention needs to be paid to the ways in which culture shapes knowledge, orientations, and perspectives."[49] For example, children from low-income families may not have access to the sorts of out-of-school experiences and resources that children from middle-class and upper-class families often do that serve to familiarize them with the traditional discourse patterns and ways of learning of science. As a result, these children come to school with different experiences with scientific thinking. Thus, simply bringing new technologies to schools in diverse communities is not enough; teaching in the classroom must also take into account the diversity of the students.

Effective ICT-based learning and assessment materials are expensive to produce but, once produced, cost little to scale up to serve large numbers of students. Traditional vendors of educational materials, however, have been hesitant to invest in sophisticated ICT-based materials, whether because of the large initial development cost, inadequate technological expertise, or fear that the market will be small. Even technology-savvy companies such as game developers have not usually viewed the educational market as promising. As a result, many of the learning materials currently available fail to exploit the full potential of ICT. Future reform efforts must take these realities into account.

A coordinated development program is needed over the next decade to produce high quality, research-based, open-access technology applications for core content in science, technology, engineering, and mathematics at all grade levels. Materials must be designed to teach and assess particular skills or concepts and tested to be classroom ready and teacher friendly. By making the materials freely available, schools will be able to divert some textbook funding to ICT equipment without increasing overall costs. Such technology development must be linked to—and where possible embedded in—the efforts recommended above to redefine science and mathematics curricula, how learning is assessed, how teaching is done, and what students can be expected to know and understand. A focused federal investment to develop and provide a demonstration library of effective open-source, technology-based curriculum resources and tools with a proven value for science and mathematics learning could stimulate schools and curriculum publishers to make the investments needed to realize the potential of instructional technology and technology-based tools on a large scale.

**RECOMMENDATION 6: Federal and state policy makers should establish a research and development cycle to sustain and improve science and mathematics education nationally.**

Too often education reforms in the United States are instituted without a solid research base. The reforms are then evaluated based on their average effect and, when the data show that they had little effect, are abandoned in favor of a new idea about what will work better. There is no opportunity to improve the intervention based on the detailed findings of the original evaluation.

In contrast, a systems-engineering approach would call for reforms or interventions to be designed based on research. Once the research-based intervention has been developed, the reformers would then identify the measures by which the intervention will be evaluated. These measures, or parameters, would be monitored and adjusted so that they are as useful as possible in improving the system's effectiveness. The reform would then be redesigned and reevaluated in a series of steps toward ever-better performance as determined by the evaluations.

This iterative cycle of research and development is needed throughout the educational system if we are to achieve the improvements we seek. All elements of the science and mathematics instructional system—curriculum, teaching and teacher preparation, assessment, support systems external to the classroom, and technology—should be subjected to this applied research and development cycle.[50] The federal government can and should play a leading role in shifting resources toward supporting design cycles that allow improvements and research insights to accumulate.[51] If such a system were implemented, our schools and policy makers would be able to stop lurching from one purported "magic bullet" to another, wasting leadership capital and the goodwill of teachers and parents.

One vehicle for carrying out such research would be multi-state or multi-district consortia.[52] We recommend that the federal government help facilitate the formation and work of such groups by offering to fund key projects as multi-state efforts. The goal is to remake the overall system by developing core learning goals, appropriate curriculum materials, and aligned assessment systems without attempting to impose national requirements. This cannot be a one-time process; it will need successive iterations to reach the high level of expectations and performance that we envision. Each consortium will have an ongoing function in maintaining, monitoring, and revising the instructional system and achievement goals they create. To be viable, they should be staffed by professionals who can do this work.[53]

Projects that produce gains should be sustained; those that do not should be discontinued. The system of formative evaluation and reengineering described above should be used to improve interventions. But, those reforms also should be subjected to periodic external evaluation of their results. If there are no gains, or the gains are too small for the cost and effort, the reforms should be discontinued. Projects that have promising outcomes at 5 years need support for 5 to 10 more years to refine their tools and build clarity on what is critical to their approach. Those that prove most effective during that period can then be broadly implemented with confidence that their impact can be replicated.

## Notes

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