Summary

Education for students in science, technology, engineering, and mathematics (STEM) has received increasing attention over the past decade with calls both for greater emphasis on these fields and for improvements in the quality of curricula and instruction. In response, numerous new instructional materials, programs, and specialized schools are emerging. While most of these initiatives address one or more of the STEM subjects separately, there are increasing calls for emphasizing connections between and among the subjects.

Advocates of more integrated approaches to K–12 STEM education argue that teaching STEM in a more connected manner, especially in the context of real-world issues, can make the STEM subjects more relevant to students and teachers. This in turn can enhance motivation for learning and improve student interest, achievement, and persistence. And these outcomes, advocates assert, will help address calls for greater workplace and college readiness as well as increase the number of students who consider a career in a STEM-related field.

Recently, both the Common Core State Standards for Mathematics (CCSSM) and the Next Generation Science Standards (NGSS) have called for more and deeper connections among the STEM subjects. The NGSS explicitly includes practices and core disciplinary ideas from engineering alongside those for science, raising the expectation that science teachers will be expected to teach science and engineering in an integrated fashion.
Despite the rise in interest in providing students with learning experiences that foster connection making across the STEM disciplines, there is little research on how best to do so or on what factors make integration more likely to increase student learning, interest, retention, achievement, or other valued outcomes. Recognizing the need for a more robust evidence base, the National Academy of Engineering (NAE) and the Board on Science Education of the National Research Council (NRC) convened a committee to examine current efforts to integrate the STEM disciplines in K–12 education and develop a research agenda that, if carried out, could provide the data needed to inform such efforts going forward.

The NAE/NRC Committee on Integrated STEM Education was charged with

- identifying and characterizing existing approaches to integrated STEM education, both in formal and after-/out-of-school settings,
- reviewing the evidence for the impact of integrated approaches on various student outcomes, and
- determining a set of priority research questions to advance understanding of integrated STEM education.

**DESCRIPTIVE FRAMEWORK**

Far from being a single, well-defined experience, integrated STEM education includes a range of different experiences that involve some degree of connection. The experiences may occur in one or several class periods, throughout a curriculum, be reflected in the organization of a single course or an entire school, or be encompassed in an out-of-school activity. Each variant of integrated STEM education suggests different planning approaches, resource needs, implementation challenges, and outcomes.

To make sense of this confusing landscape, the committee developed a descriptive framework. The framework is meant to provide a common perspective and vocabulary for researchers, practitioners, and others to identify, discuss, and investigate specific integrated STEM initiatives within the K–12 education system of the United States. Although potentially a very large number of variables could be incorporated into such a framework, the committee chose to focus on four high-level features: goals, outcomes, nature of integration, and implementation.
SUMMARY

Goals identified in the framework include building STEM literacy and 21st century competencies; developing a STEM-capable workforce; and boosting interest and engagement in STEM. In terms of outcomes, the framework considers learning and achievement; STEM course taking; STEM-related employment; development of “STEM identity”; and the ability to transfer understanding across STEM disciplines. Regarding the nature and scope of integration, the framework addresses which subjects are connected; which disciplines are dominant; and the duration, size, and complexity of an initiative. With respect to implementation, the framework focuses on instructional designs involving problem-based learning and engineering design; the type of educator supports present, such as pre- and in-service professional development and development of professional learning communities; and adjustments to the learning environment, such as extended class periods, extended lesson planning, team teaching, and partnering between STEM educators working in and outside of schools.

RESEARCH ON THE IMPACTS OF INTEGRATED STEM EDUCATION

In reviewing the literature, the committee focused on research related to the potential impact of integrated STEM education in two areas: learning and achievement, and interest and identity. Looking across studies, the integration of STEM concepts and practices has the promise to lead to increased conceptual learning within the disciplines. However, the positive impact on learning appears to differ for science and mathematics, with less evidence of a positive impact on mathematics outcomes, based on current assessments for those subject areas, which might not fully capture integrated learning in STEM. For both science and mathematics, the impact on learning and achievement depends on the approach to integration and the kinds of supports that are embedded in the experience and provided through instruction. Integrated STEM education also shows promise of supporting knowledge gains in engineering and technology. Given the small number of studies, generally small sample sizes, and reliance on pre- and post-study designs, however, these potentially promising findings must be interpreted cautiously.

There are indications that integrated STEM experiences can support interest development, but research studies vary considerably in quality and often do not take into account the different phases of interest development, limiting what can be concluded from this work. Integrated STEM education
experiences may provide opportunities for students to engage in STEM in ways that potentially transform their identities with respect to the STEM subjects. This effect may be particularly strong for populations that have historically struggled in STEM classes and that are historically underrepresented in STEM programs in higher education and STEM professions. However, studies on identity in the context of integrated STEM education are few, and most of them are qualitative in nature. In addition, outcomes focused on interest and identity are more commonly measured in after- and out-of-school settings than in the context of formal classrooms.

**IMPLICATIONS OF RESEARCH FOR THE DESIGN OF INTEGRATED STEM EDUCATION**

In addition to reviewing research related to outcomes, the committee examined research from cognitive psychology, the learning sciences, and educational psychology—as well as from studies focused specifically on integrated STEM education—for clues about factors that may help explain the potential benefits and challenges posed by integration.

From the perspective of what is currently known about cognition and learning, integration may be effective because basic qualities of cognition favor connected concepts over unconnected concepts so they are better organized for future retrieval and meaning making. It is these connected knowledge structures that can support learners’ ability to transfer understanding and competencies to new or unfamiliar situations. In addition, being able to represent the same concept within and across disciplines in multiple ways—for example, visually, in physical form, and in writing—can facilitate learning, research shows. But integration can also impede learning because it can place excessive demands on resource-limited cognitive processes, such as attention and working memory.

Though fundamental to all learning experiences, social and cultural experiences such as those which require students to work with each other and actively engage in discussion, joint decision making, and collaborative problem solving may be particularly important in integrated learning. Some social processes can support learning through deliberate efforts to convey knowledge and strategies to children. Techniques such as scaffolding and peer collaboration can help students be successful with challenging tasks and move beyond their current state of knowledge.
SUMMARY

One hallmark of integrated approaches, though not unique to them, is the use of real-world situations or problems. Although these contexts can bring STEM fields alive for students and have the potential to deepen their learning, they may also pose challenges to students. For instance, there is evidence that use of detailed concrete situations that include rich perceptual information can prevent students from identifying the abstract structural characteristics that are needed to transfer their experiences to other settings.

Taken together, the findings from research have implications for the design of integrated STEM education initiatives. Three key implications are:

1. Integration should be made explicit. Observations in a number of STEM settings show that integration across representations and materials, as well as over the arc of multi-day units, is not spontaneously made by students and therefore cannot be assumed to take place. This highlights the importance of designing integrated experiences that provide intentional and explicit support for students to build knowledge and skill both within the disciplines and across disciplines. In many integrated STEM experiences, such supports are missing or only implicitly embedded within the classroom activities or the CAD software, measurement instruments, and computational tools used in the classroom.

2. Students’ knowledge in individual disciplines must be supported. Connecting ideas across disciplines is challenging when students have little or no understanding of the relevant ideas in the individual disciplines. Also, students do not always or naturally use their disciplinary knowledge in integrated contexts. Students will thus need support to elicit the relevant scientific or mathematical ideas in an engineering or technological design context, to connect those ideas productively, and to reorganize their own ideas in ways that come to reflect normative, scientific ideas and practices.

3. More integration is not necessarily better. The potential benefits and challenges of making connections across the STEM subjects suggest the importance of a measured, strategic approach to implementing integrated STEM education that accounts for the potential trade-offs in cognition and learning.
CONTEXT FOR IMPLEMENTING INTEGRATED STEM EDUCATION EXPERIENCES

Three contextual factors are likely to present both opportunities and challenges to the implementation of integrated STEM education at the K–12 level: standards, assessments, and educator supports.

The recently published CCSSM and the NGSS have the potential to focus educators on helping students make connections across the disciplines. The committee recognizes that not all states will adopt the CCSSM or the NGSS. However, the underlying principles that inform both sets of standards are likely to influence approaches to mathematics and science education, even in those states that do not formally adopt the new standards. These underlying principles include active engagement of students in authentic tasks, support for development of conceptual knowledge and reasoning, and application of knowledge in real-world contexts.

One challenge of taking advantage of the opportunities for integration presented by the CCSSM and NGSS is attending to developing disciplinary knowledge while also supporting students in making connections across disciplines. This concern is highlighted by research showing that curricula integrating mathematics or science with other STEM subjects are less likely to produce positive learning outcomes in mathematics than they are in science, although effect sizes can vary greatly depending on how science and mathematics are offered (sequentially, in parallel, together and separately, or together either with one subject as the dominant theme of the lesson or with both subjects completely integrated—see Chapter 3 for additional details). A second challenge is presented by the partial overlap in some of the practices identified in the CCSSM and NGSS, where the same terms have different meanings for experts in different fields. For example, argumentation in mathematics differs from argumentation in science. In order for students to engage in argumentation in both disciplines, they will need to understand what makes scientific arguments different from mathematical arguments.

Assessments—from formative assessment at the classroom level to large-scale state assessment for accountability—have the potential to limit the extent to which integrated STEM can be incorporated into K–12 education. Existing assessments tend to focus on knowledge in a single discipline. Furthermore, they typically focus on content knowledge alone and give little attention to the practices in the disciplines and applications of knowledge. In terms of innovative approaches, large-scale assessments pose the biggest
challenges, though some innovative examples do exist, such as the National Assessment of Educational Progress (NAEP) probe assessment of technology and engineering literacy being fielded in a sample of US eighth graders in 2014. Other potential models of assessments that might be adapted to address STEM integration include the recently restructured advanced placement (AP) biology exam from the College Board and the computer-based tasks on the 2009 NAEP Interactive Computer and Hands-On Tasks Science Assessment. More generally, digital and networking technologies have the potential to expand the range of outcomes (e.g., progressions of integrated STEM learning) that can be measured.

The expertise of educators working in classrooms and in after-/out-of-school settings is a key factor—some would say the key factor—in determining whether integrated STEM education can be done in ways that produce positive outcomes for students. One limiting factor to teacher effectiveness and self-efficacy is teachers’ content knowledge in the subjects being taught. For example, most K–12 science and mathematics teachers have taken fewer courses in the subject area(s) in which they were prepared than are recommended by their respective teacher professional associations, and many have taken few courses in other areas of STEM. The small amount of available data for K–12 technology teachers, many of whom are providing engineering instruction, suggests their preparation in mathematics and science is quite limited. Furthermore, surveys find that teachers of K–12 mathematics and science lack confidence in their ability to teach engineering.

Apart from subject-specific content knowledge, the ability and confidence to teach across subjects will be critical for educators called upon to deliver integrated K–12 STEM education. Educators will need to know how to provide instructional supports that help students recognize connections between disciplines, and they will need to support students’ developing proficiency in individual subjects in ways that complement students’ learning through integrated activities. At the present time, very few teacher education programs around the country are making efforts to prepare prospective teachers with appropriate content knowledge in more than one STEM subject. A larger number of programs provides in-service professional development related to integrated STEM education; most of these efforts are connected to existing curriculum projects.

Although perhaps obvious, it is worth noting that many of the changes likely to be needed to successfully implement integrated STEM education will require additional financial resources. Money, as well as time and planning, will be required to help educators acquire content and pedagogical
content knowledge in disciplinary areas beyond their previous education or experience. And funds will be needed to design, pilot test, and implement any large-scale assessment.

RECOMMENDATIONS

The committee developed 10 recommendations: two directed at multiple stakeholders in K–12 integrated STEM education; four directed at those involved in designing integrated STEM education initiatives; one intended for those charged with developing assessments; and three that target researchers. In the full report, the recommendations appear in Chapter 6 in an order different from that presented here. For clarity, the number of the recommendation as it appears in the full report is indicated.

Recommendations for Multiple Stakeholders

Researchers, program designers, and practitioners focused on integrated STEM education, and the professional organizations that represent them, need to develop a common language to describe their work. This report can serve as a starting point. (Recommendation 2)

To allow for continuous and meaningful improvement, designers of integrated STEM education initiatives, those charged with implementing such efforts, and organizations that fund the interventions should explicitly ground their efforts in an iterative model of educational improvement. (Recommendation 10)

Recommendations for Designers of Integrated STEM Experiences

Designers of integrated STEM education initiatives need to be explicit about the goals they aim to achieve and design the integrated STEM experience purposefully to achieve these goals. They also need to better articulate their hypotheses about why and how a particular integrated STEM experience will lead to particular outcomes and how those outcomes should be measured. (Recommendation 5)
SUMMARY

Designers of integrated STEM education initiatives need to build in opportunities that make STEM connections explicit to students and educators (e.g., through appropriate scaffolding and sufficient opportunities to engage in activities that address connected ideas). (Recommendation 6)

Designers of integrated STEM experiences need to attend to the learning goals and learning progressions in the individual STEM subjects so as not to inadvertently undermine student learning in those subjects. (Recommendation 7)

Programs that prepare people to deliver integrated STEM instruction need to provide experiences that help these educators identify and make explicit to their students connections among the disciplines. These educators will also need opportunities and training to work collaboratively with their colleagues, and in some cases administrators or curriculum coordinators will need to play a role in creating these opportunities. Finally, some forms of professional development may need to be designed as partnerships among between educators, STEM professionals, and researchers. (Recommendation 8)

Recommendation for Assessment Developers

Organizations with expertise in assessment research and development should create assessments appropriate to measuring the various learning and affective outcomes of integrated STEM education. This work should involve not only the modification of existing tools and techniques but also exploration of novel approaches. Federal agencies with a major role in supporting STEM education in the United States, such as the Department of Education and the National Science Foundation, should consider supporting these efforts. (Recommendation 9)

Recommendations for Researchers

In future studies of integrated STEM education, researchers need to document the curriculum, program, or other intervention in greater detail, with particular attention to the nature of the integration and how it was supported. When reporting on outcomes, researchers should be explicit about the nature of the integration, the types of scaffolds and instructional designs used, and the type of evidence collected to demonstrate whether the goals of the intervention were achieved. Specific learning mechanisms should be articulated and supporting evidence provided for them. (Recommendation 1)
Study outcomes should be identified from the outset based on clearly articulated hypotheses about the mechanisms by which integrated STEM education supports learning, thinking, interest, identity, and persistence. Measures should be selected or developed based on these outcomes. (Recommendation 3)

Research on integrated STEM education that is focused on interest and identity should include more longitudinal studies, use multiple methods, including design experiments, and address diversity and equity. (Recommendation 4)

RESEARCH AGENDA

To help guide future research, the committee posed questions aligned to the descriptive framework that, if addressed, have the potential to provide useful data for advancing the quality and effectiveness of integrated K–12 STEM education in the United States. The questions fall under three broad categories referenced earlier: outcomes of integrated STEM education, the nature of integrated STEM education, and design and implementation of integrated STEM education. Within each category, specific research questions are identified. For example, “What instructional approaches or contexts are most likely to lead to student outcomes related to making connections between and among the STEM disciplines?” And, “How should integrated STEM experiences be designed to account for educators’ and students’ varying levels of experience with integrated learning and STEM content?” Taken together, the questions comprise a research agenda for integrated STEM education.

FINAL THOUGHTS

There is much more that can and should be learned about the outcomes, nature, and design and implementation of integrated STEM education. This should not discourage those designing, implementing, or studying integrated STEM education programs. On the contrary, our findings, recommendations, and research agenda strongly suggest the potential of some forms of integrated STEM education to make a positive difference in learning, interest, and other valued outcomes.

The level of evidence gathered by the committee is not sufficient to suggest that integrated STEM education could or should replace high-quality education focused on individual STEM subjects. Indeed, integrated STEM education requires that students hone their expertise in the very disciplines
that are being connected. However, parts of the STEM education community are already moving toward integration. This suggests that the energy, creativity, and resources of researchers, practitioners, and concerned funders should be directed at generating more thoughtful, high-quality, and evidence-based work exploring the benefits and limitations of integrated STEM education. Given the inherent complexities, it will not be a surprise to find that designing and documenting effective initiatives will be time consuming and expensive. Despite these challenges, the possibility of adding new tools to the STEM education toolbox is exciting and should be coupled with rigorous research and assessment of implementation efforts.