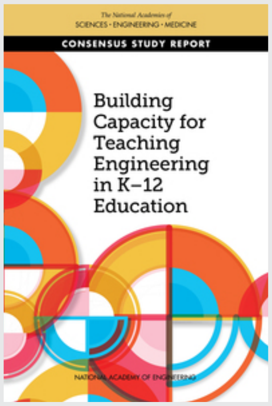

Building Capacity for Teaching Engineering in K-12 Education (2020)

DETAILS

186 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-49942-2 | DOI 10.17226/25612

CONTRIBUTORS

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SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2020. *Building Capacity for Teaching Engineering in K-12 Education*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25612.

PREPUBLICATION COPY, UNCORRECTED PROOFS

BUILDING CAPACITY FOR TEACHING ENGINEERING IN K–12 EDUCATION

Committee on Educator Capacity Building in K–12 Engineering Education

National Academy of Engineering
Board on Science Education
Division of Behavioral and Social Sciences and Education

A Consensus Study Report of
The National Academies of
SCIENCES • ENGINEERING • MEDICINE

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

PREPUBLICATION COPY, UNCORRECTED PROOFS

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This activity was supported by the National Science Foundation under Grant No. (1540253). Additional funding was provided by the Samueli Foundation and Robin K. and Rose M. McGuire. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

International Standard Book Number-13: 978-0-309-XXXXX-X
International Standard Book Number-10: 0-309-XXXXX-X
Digital Object Identifier: https://doi.org/10.17226/25612
Library of Congress Control Number:

Additional copies of this publication are available from the National Academies Press, 500 Fifth Street NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; www.nap.edu.

Printed in the United States of America

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2020. *Building Capacity for Teaching Engineering in K–12 Education*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25612.

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Acknowledgments

This Consensus Study Report represents the work of many individuals, especially those who served on the committee and participated in the committee's open sessions. The first thanks are to the committee members for their deep knowledge and contributions to the study.

The committee employed several consultants who collected and analyzed data that appears in the report. Thanks go to Jackie DeLisi, Lisa Marco-Bujosa, and Quincy Chang (Education Development Center); Michael de Miranda (Texas A&M University); and Daniel Kuehn (Urban Institute).

The committee benefited from presentations by several individuals who participated in our fact-finding workshops in April and August of 2017. In addition to committee members and consultants, workshop presenters were David Evans (National Science Teaching Association), Okhee Lee (New York University), Douglas Clements (University of Denver), James Basham (University of Kansas), Matt Irvin (University of South Carolina), Christine Cunningham (then of Engineering is Elementary), Bernie Zubrowski (EDC), Jose Rivas (Lennox Math, Science and Technology Academy), Amy Morriss (Academy of Our Lady), Brandon Hernandez (Olathe Public Schools Engineering Academy), Glenn Bradbury (Bozeman High School), Julia Harth (HB Whitehorne Middle School), Christopher Kohnke (Colbert Elementary School), Adrianne Wheeler (Project SYNCERE), Angie Brayford (SHINE), Jim Short (Carnegie Corporation of New York), Pam Lottero-Perdue (Towson University), Karen Worth (Wheelock College), Ken Welty (University of Wisconsin–Stout), Robin Adams (Purdue University), Tamara Moore (Purdue University), Deidre Sessoms (CSU-Sacramento), Pat Yongpradit (Code.org), Maria Hyler (Learning Policy Institute), Madelyn Gardner (Learning Policy Institute), Jennifer Ryan Crozie (IBM International Foundation), and Maura Banta (IBM).

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Paul R. Gray, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, and Joseph Krajcik, College of Natural Science and College of Education, Michigan State University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Thanks are also due to the project staff: Greg Pearson, Beth Cady, Kenne Dibner, Cameron Fletcher, Michael Holzer, Maribeth Keitz, Jay Labov, Kirsten Sampson-Snyder, Heidi Schweingruber, and Jason Williams.

Ellen Kullman (*Chair*), CEO and president of Carbon, CEO and chair (retired) DuPont

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Summary

Engineering is emerging as an important topic in US K–12 education. Although not as prevalent as other, more established school subjects, it is finding its way into standards, instructional materials, and assessments. The *Next Generation Science Standards* (NGSS; NGSS Lead States 2013), for instance, envision the integration of engineering concepts and practices with those from science, and the District of Columbia and nearly 80 percent of states have either adopted or adapted the standards. As another example, the Department of Education recently developed and administered a national assessment of engineering and technology literacy (NAEP 2016), which is providing insights into what US K–12 students know and can do in these important subjects. These and related developments are occurring in the context of broad, national support for improving K–12 student access and achievement in all STEM (science, technology, engineering, and mathematics) areas, which are the building blocks of technological innovation, economic growth, civic participation, national security, and quality of life.

As the landscape of K–12 engineering education continues to evolve, educators, administrators, and policymakers must consider the capacity of the US education system to meet current and anticipated needs for K–12 teachers of engineering. What do such educators need to know and be able to do in order to be effective, and where and how might they develop such expertise?

To help answer these and related questions, the National Academy of Engineering and the Board on Science Education of the National Academies of Sciences, Engineering, and Medicine convened an expert committee to conduct extensive data gathering and analysis, including a thorough review of the research literature, surveys, and input from experts. The goal of the project was to understand current and anticipated future needs for engineering-literate K–12 educators in the United States and suggest how to meet these needs. The committee charge included eight questions in three areas:

<u>The Preparation of K–12 Engineering Educators</u>

1. What is known from education and learning sciences research about effective preparation of K–12 educators to teach about engineering?
2. What appear to be the most promising educator-preparation practices currently in use?
3. What additional research is needed to improve and expand effective approaches for preparing K–12 engineering educators?

<u>Professional Pathways for K–12 Engineering Educators</u>

4. What formal (e.g., state certification) and informal (e.g., “badging”) mechanisms are being used to recognize expertise and support career pathway options for K–12 teachers of engineering?
5. What formal and informal credentialing mechanisms from domains other than education might be adapted or adopted to recognize expertise and support career pathway options for K–12 teachers of engineering?

6. What are the practical and policy impediments to instituting effective credentialing for K–12 engineering educators, and how they might be addressed?

The Role of Higher Education

7. What roles do or might postsecondary institutions, including but not limited to four-year engineering and engineering technology programs, play in the preparation of K–12 engineering educators?
8. What are the practical and policy impediments to involving higher education in the preparation of K–12 engineering educators, and how might they be addressed?

Although not called out in the charge, the committee recognizes that informal education is a large and important component of the education system. In part due to lack of information about educator professional learning in informal settings, however, the report treats informal education in a very limited way.

ENGINEERING AND K–12 EDUCATION

Engineering is both a method for solving problems and a body of knowledge about the design and creation of human-made products and processes. Like many human endeavors, engineering has a number of essential qualities. It uses a systematic approach to understand and address problems; relies on large, diverse, and often geographically dispersed teams of individuals; employs repeated cycles of testing, data collection, analysis, and improvement to reach an optimal solution; accepts initial design failures as important and necessary to improving the solution; and is attentive to social and ethical concerns.

Engineering design is the universal problem-solving process used by engineers. Key concepts embedded in the design process include specifications and constraints, which establish the parameters of the solution space; optimization and trade-offs, which help engineers choose among potentially competing solutions; modeling and analysis, used to understand and improve the behavior of prototypes or elements of a potential solution; and systems, the discrete elements of a solution that are designed to work together in interdependent ways.

Engineering, science, and mathematics are interdependent disciplines, and advances in one often enable progress in another. Although not strictly defined as a discipline, technology encompasses the entire system of knowledge, processes, devices, people, and organizations involved in the creation and operation of technological artifacts, as well as the artifacts themselves. Much of modern technology is a product of engineering, science, and mathematics, and people in all three fields use technological tools. Engineering and science share a number of similarities but are also different in some important ways.

In K–12 settings, engineering is situated among STEM subjects in one of two ways: in the foreground, with science, mathematics, or both subjects in a supporting role; or in a supporting role, with science or mathematics, or both, in the foreground. In the first case, science and mathematics serve engineering, primarily by supporting engineering design solutions. In the second case, engineering serves science and mathematics, primarily by providing context to improve student understanding of science and mathematics. Although the two framings of K–12 engineering education share characteristics, their different emphases on engineering can lead to different learning objectives for students and, by implication, for their educators. The engineering design process plays a central role in K–12 curriculum and instruction.

GOALS OF K–12 ENGINEERING EDUCATION

The committee reviewed extant curricula and programs as well as related research and discerned four goals of K–12 engineering education:

(1) develop engineering literacy;
(2) improve mathematics and science achievement through the integration of concepts and practices across the STEM fields;
(3) improve college and career readiness; and,
(4) for a small percentage of students, prepare for matriculation in postsecondary engineering programs.

The four goals are not mutually exclusive. With the exception of preparing for matriculation in postsecondary engineering, which targets high school, the goals apply across the K–12 grades. While these goals are student focused, they have implications for how teachers of engineering should be prepared and supported.

Engineering literacy includes understanding of key concepts in engineering and a basic ability to engage in the engineering design process. Ideally, engineering-literate students (and their teachers) should also appreciate the influence of engineering on society and how engineering is different from science in its application to personal, social, and cultural situations. Finally, engineering literacy addresses issues related to technology.

All teachers of K–12 engineering should be able to teach to the goal of engineering literacy. This implies that they will need knowledge and skills equivalent to (and, preferably, more advanced than) those of their students. Educators aiming to make use of mathematics and science in their engineering teaching need pedagogical content knowledge relevant to the integration of these subjects with engineering design. K–12 engineering educators involved in preparing students to enter college engineering programs need to master certain advanced concepts in mathematics and science. The latter might be accomplished through postsecondary engineering coursework, an engineering degree, industry experience, or some combination.

Achieving the goals will involve addressing issues of equity and inclusion, an especially relevant challenge given the longstanding lack of diversity within postsecondary engineering education and the engineering workforce.

THE WORKFORCE OF K–12 TEACHERS OF ENGINEERING

Limitations of available data make it very difficult to assess the extent to which US K–12 educators are teaching engineering. One data source is the federal National Teacher and Principal Survey (NTPS). According to NTPS, approximately 8,700 public school teachers taught “engineering” during the 2015–16 school year; another 19,000 taught “construction trades, engineering, or science technologies”; and 41,000 taught “industrial arts or technology education,” a field that is evolving to include instruction in engineering. Another data source is the 2018 National Survey of Science and Mathematics Education (NSSME) (Banilower et al. 2018), which found that 46 percent of public and private high schools in the sample offered at least one engineering course. This suggests that as many as 14,000 high school educators taught at least one such course that year.[1] (For comparison, there are roughly 232,000 secondary science teachers working in public schools.)

Along with knowledge of how to teach, or pedagogy, teacher content knowledge is a critical component of effective teaching, and college degrees and course taking often serve as proxies for this knowledge. Just 6.3 percent of teachers of “engineering” and “construction trades, engineering, or science technologies” (combined) in the NTPS sample reported engineering as their first major, and only 1 percent of “industrial arts or technology education” teachers did so. In terms of coursework, NSSME (NSSME; Banilower et al. 2018, table 2.7) found that 3, 10, and 13 percent of elementary, middle, and high school science teachers, respectively, had taken at least one college course in engineering.

There are very few programs that prepare prospective K–12 teachers of engineering. Some are in the field of technology education, which had 41 active teacher preparation programs as of 2017. The number of these programs has been declining for many years, and there is great variability in the extent of coursework in engineering and relevant pedagogy they provide. Programs that allow undergraduate students to combine a major in a STEM field with education coursework and certification to teach are another source of potential new K–12 teachers of engineering. The largest such initiative is the UTeach program, which has been adopted by over 40 universities. As of 2018 the program had graduated over 4,500 students, nearly 90 percent of whom have become K–12 teachers. The vast majority of these graduates have degrees in science or mathematics; 3 percent have degrees in engineering. In addition to the UTeach initiatives, another roughly half-dozen universities across the country provide engineering coursework to students studying to become K–12 teachers.

The committee was not able to determine the extent to which programs preparing new K–12 science teachers incorporate instruction and experiences in engineering. This is an important issue, given NGSS’s call for engineering concepts and practices to be integrated with those of science. Recently revised standards for science teacher preparation programs (NSTA and ASTE 2019) call out the importance of developing future teachers’ knowledge of engineering and of appropriate pedagogy.

One key element along the professional pathway to a career in teaching is credentialing. The most common credential for teachers who might be expected to teach engineering was for “technology education” (part of career and technical education, or CTE) and was available in 27 states. A number of states offer other specialized CTE credentials across a range of technical topics, including engineering. A small number of states include engineering requirements in credentials for teachers of STEM. For a variety of reasons, it was difficult for the committee to determine the specifics of the engineering-related knowledge required for many certification options.

PROFESSIONAL LEARNING

A number of research-based frameworks spell out the general learning needs of K–12 educators, and many elements of these general frameworks are relevant to the preparation of K–12 teachers of engineering. But these educators also have unique learning needs. One document that spells out those needs is the 2014 *Standards for Preparation and Professional Development of*

[1] This number reflects the assumption, based on Mathews (2011), that there are about 23,000 public and 7,300 private high schools in the United States.

Teachers of Engineering,[2] developed by a group of K–12 engineering professional development providers. The standards call for K–12 teachers of engineering to

- be literate with respect to engineering design and engineering careers;
- acquire relevant pedagogical content knowledge, such as how teaching and learning in engineering is similar to, and different from, teaching and learning in science and/or mathematics; and
- appreciate how problem solving and engineering design can contextualize teaching standards of learning in other subjects (e.g., science, mathematics, language arts, reading).

The differing goals for K–12 engineering education mean that teachers of engineering may need to master concepts and practices that go beyond basic engineering literacy. When the instructional context warrants, for example, teachers of engineering will need to help students experience STEM education in a more integrated way. This capability will be important not only for technology educators, who need to support students' use of science and mathematics to address engineering challenges, but also for science and mathematics teachers tasked with integrating engineering in their instruction or, indeed, for teachers of any subject who want their students to learn engineering. The breadth and depth of science and mathematics knowledge needed by K–12 teachers of engineering will vary according to grade, the specific curriculum, and instructional goals.

Another important area of teacher learning is knowledge about how to teach specific concepts within a subject, or pedagogical content knowledge (PCK). An important element of PCK for teachers of engineering is to understand and leverage the diversity of K-12 students' backgrounds and experiences. Given engineering's long-standing poor track record of attracting and retaining underrepresented minorities and women in education and the workplace, inclusive teaching methods may have special value in K–12 engineering education.

Researchers and practitioners have made strides in delineating aspects the knowledge base relevant to the preparation of teachers of engineering, but far less progress has been made determining how this knowledge base differs for teachers of different grades; how knowledge builds on itself over time (progression); and what preparation in science and mathematics teachers of engineering should have (and how this preparation might vary according to grade and primary subject taught).

Opportunities for meeting the learning needs of K–12 educators may occur during initial preparation, early career induction, and ongoing professional development. The committee found no empirical evidence that differentiated the learning opportunities needed by K–12 teachers of engineering at different stages of their careers. However, research on quality teacher preparation, induction, and professional development in other subject areas points to a number of learning experiences that can improve teachers' subject-matter knowledge and PCK and that correlate with student performance. It is reasonable to expect that similar learning experiences for K–12 teachers of engineering would lead to similar improvements in outcomes.

Educators with formal, academic preparation in the subject they teach are likely to have a better grasp of domain-specific content relevant to student learning goals. As noted, there are very few opportunities for prospective K–12 teachers to take coursework in engineering or otherwise gain knowledge of the field. With respect to programs that do provide such

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[2] Available at https://www.asee.org/documents/papers-and-publications/papers/outreach/Standards_for_Preparation_and_Professional_Development.pdf.

opportunities, the committee's review of the literature uncovered no information about how the content and organization of the curriculum might influence educator preparation to teach K-12 engineering. The committee was also unable to determine the extent to which programs preparing new science teachers include engineering content and instruction, which might help these teachers implement the engineering components of NGSS.

Professional development can help teachers acquire new knowledge, adapt to shifting policies, and hone their craft once they have entered the profession. Considerable research has elucidated factors generally associated with high-quality professional development; these include active teacher engagement, a focus on content and instructional practices demonstrated to be effective, experiences during and outside of the school day, and building the capacity of teams of teachers. For K–12 engineering specifically, a few studies pointed to potentially promising practices; for example, curriculum design–based professional development, in which teachers learn content by creating instructional materials, can provide educators with both engineering content knowledge and an active learning experience. Professional development that brings teachers of engineering together in communities of practice, either in person or online, may also provide benefit.

CREATING A SYSTEM OF SUPPORT FOR K–12 TEACHERS OF ENGINEERING

The capacity to meet the objectives of any reform effort in K–12 education depends on more than the competence and confidence of individual teachers. It also depends on the many components of the larger system within which these educators work. Policies, programs, and practices at the federal, state, district, and school levels influence the extent and quality of preparation of K–12 teachers of engineering. Other actors, including higher education and the education research community, will also impact the nation's ability to prepare K–12 teachers of engineering

The current version of the federal Elementary and Secondary Education Act, the "Every Student Succeeds Act" (ESSA), allows states to use federal dollars to fund professional development of K–12 teachers of engineering, develop alternative certification pathways, and support engineering teacher leaders. However, states are not required to spend their federal funding in these areas. ESSA requires states to assess students' science achievement at three points during their K–12 careers. Because the majority of states have either adopted or adapted NGSS, these assessments presumably will need to probe students' grasp of engineering ideas and practices. Under ESSA, states may use federal dollars to integrate engineering design skills and practices in their science assessments, but this also is not mandated, and the committee found no evidence that new state science assessments are attending to specific ideas and practices in engineering.

Educational standards can serve as an important policy lever in reform efforts, particularly when aligned with curriculum, assessment, and teacher professional learning. The development and implementation of standards documents falls to the states. Standards in technology and science education set expectations that students will learn engineering ideas and practices, and standards governing science teacher preparation programs suggest that prospective K–12 science teachers should understand engineering design and its relevance to science teaching. The committee was not able to determine the extent to which states are implementing the engineering-related elements of student learning standards or whether postsecondary teacher education programs are engaging prospective science teachers in engineering concepts and practices.

Higher education can support high-quality teacher professional learning in engineering through programs that bring undergraduate or graduate engineering students into the classroom or bring teachers on campus to learn about engineering. Postsecondary engineering education institutions, which include both schools of engineering and schools of engineering technology, can supply the content expertise needed by programs that prepare new teachers of K–12 engineering, as can industry programs for teachers. Expanding and improving teacher preparation programs may require collaborations between engineers, teacher educators, and teachers.

The evidence base that might inform effective approaches to preparing K–12 teachers of engineering is thin and uneven, in part because there are few education researchers and social and learning scientists studying issues in K–12 engineering. Funding for K–12 engineering education research exists, but generally at lower levels than research on K–12 education in other STEM subjects. Encouragingly, a growing number of schools of engineering are establishing departments of engineering education, many of which conduct research on topics relevant to teaching engineering at the K–12 level. At least two peer-reviewed journals publish findings from research on K–12 engineering education.

RECOMMENDATIONS

Based on its data collection and analysis, the committee developed 10 recommendations for improving the preparation of K–12 teachers of engineering in the United States. Every recommendation calls for action by one or more stakeholders, and each is supported by one or more conclusions, which appear in the full report.

RECOMMENDATION 1: To better understand the extent to which US K–12 educators are teaching engineering, the National Center for Education Statistics should revise the National Teacher and Principal Survey so that (1) answer choices for items that query respondents about teaching assignments and certification do not combine engineering with other fields, and (2) respondents can indicate whether they are engaged in teaching engineering less than full-time or as other than a main teaching assignment (e.g., as part of a science course).

RECOMMENDATON 2: To begin to address the systemic lack of capacity to prepare preservice K–12 teachers of engineering, federal agencies, such as the Department of Education and National Science Foundation, and private foundations with an interest in STEM education should convene a collaborative dialogue among K–12 STEM educators, leaders at organizations involved in the preparation of K–12 STEM educators, colleges of education, colleges of engineering and engineering technology, postsecondary science departments, K–12 teacher accrediting bodies, state departments of education, and technology-focused industry. The goal should be to identify practicable steps that the stakeholders and others can take to address the capacity issue.

RECOMMENDATION 3: Programs that prepare prospective teachers of engineering need to make greater efforts to recruit and retain teacher candidates from populations currently

underrepresented in STEM education and careers. Likewise, professional development programs should proactively encourage the participation of teachers with these characteristics. Programs for both prospective and practicing teachers should explicitly include instruction on the use of inclusive pedagogies.

<u>RECOMMENDATION 4</u>: In the short term, both providers of professional development opportunities and educators of prospective K–12 teachers of engineering should align their work with guidance documents that draw on the most up to date understanding of research and best practices in teacher education and professional development. As new knowledge accumulates about the professional learning of K-12 teachers of engineering, adjustments in programs should reflect new insights gained from rigorous, high quality scholarship

<u>RECOMMENDATION 5</u>: As evidence accumulates about effective approaches to preparing K–12 teachers of engineering, it will be important to establish formal accreditation guidelines for K–12 engineering educator preparation programs, such as those developed by the Council for the Accreditation of Educator Preparation. The National Science Teaching Association, International Technology and Engineering Educators Association, and American Society for Engineering Education should work together to determine the appropriate content for such guidelines. Such an effort should take account of new NGSS-aligned accreditation standards for science teacher education programs, which become effective in 2020 and include student learning expectations related to engineering. It should also consider how the guidance needs to vary based on the grade level to be taught.

<u>RECOMMENDATION 6</u>: Programs that prepare preservice K–12 science educators or provide professional learning to in-service science teachers need to address the call in the *Framework* and NGSS for students to connect their science learning to engineering ideas and practices. To this end, the Association for Science Teacher Education, National Science Teaching Association, and American Society for Engineering Education should work together to assist these programs in identifying and implementing actions that will fulfill the engineering components of the new vision for K–12 science education.

<u>RECOMMENDATION 7</u>: Postsecondary engineering and engineering technology programs should partner with schools/colleges of education to design and implement curriculum for the preparation of K–12 teachers of engineering. Such efforts should be conducted in consultation with teacher professional organizations that have a stake in K–12 engineering, such as the International Technology and Engineering Educators Association and the National Science Teaching Association, as well as the American Society for Engineering Education.

<u>RECOMMENDATION 8</u>: States should work together to reach high-level agreement about what constitutes appropriate preparation and credentialing for teachers of engineering at various grade levels and what education and work-related pathways satisfy the credential process. The Council of Chief State School Officers should organize such discussions, in consultation with appropriate science and engineering professional societies and test development organizations.

RECOMMENDATION 9: Federal agencies, higher education institutions, state education agencies, industry, informal learning institutions, cultural and community organizations, and other stakeholders in the preparation of K–12 teachers of engineering should work in partnership with the schools and educators targeted by the interventions. When possible, such partnerships should leverage the expertise of teacher leaders in K–12 engineering education. Investments by these stakeholders should be allocated and used in ways that are consistent with findings from education, social science, and learning sciences research as well as the guidance provided by relevant policy documents.

RECOMMENDATION 10: Federal agencies, such as the National Science Foundation and Department of Education, with a role in supporting K–12 STEM education should fund research on topics relevant to the professional development of practicing and the education of prospective K–12 teachers of engineering. To the extent practicable, the efforts should take advantage of methods, such as design research, that encourage collaboration with stakeholders and existing reform efforts.

Pressing issues include:

- **Describe the subject-matter content knowledge and pedagogical content knowledge required for high-quality K–12 engineering education and how this knowledge varies across grade levels.**
- **Describe pedagogical approaches and specific instructional practices that effectively support students' integration of engineering with concepts and practices from the other STEM subjects.**
- **Document student learning progressions, age-appropriate expectations for engineering design thinking, and student conceptions in engineering, which will have implications for how K–12 educators at different grade levels are prepared and supported.**
- **Develop valid measures of teacher knowledge and instruction, as well as of student outcomes, that can be used to judge the effects of K–12 engineering educator preparation and professional learning programs.**
- **Characterize the current cadre of educators of K-12 teachers of engineering and their learning needs.**

FINAL THOUGHTS

The statement of task charged the committee with examining issues related to the preparation of K–12 teachers of engineering, a new, evolving, and important segment of the US STEM education workforce. As we hope this report makes clear, there is considerable potential value in engaging K-12 students in the concepts, practices, and habits of mind of engineering. Ideally, teachers responsible for providing that engagement—whether from a foundation of engineering, technology education, science, or some other subject—should be engineering literate. They should also have the pedagogical content knowledge to guide students through the challenges and rewards of using the engineering design process and in the appropriate application of concepts and practices from science and mathematics. Findings from high-quality research in education should inform the professional learning of these educators.

For reasons historical and structural, the current situation is far from this ideal. As this report points out, there are very few postsecondary programs educating prospective K–12 teachers of engineering, and state mechanisms for recognizing these teachers' engineering knowledge, where they exist, vary widely. There are a number of K–12 engineering professional development initiatives, some of which have reached considerable scale. Most of these efforts are small, however, and not grounded in evidence from research. In short, there are few professional pathways for those hoping to become K–12 teachers of engineering.

If this report can do one thing, we hope it will be to alert constituencies with a stake in US STEM education to the mismatch between the need for engineering-literate K–12 teachers and the education system's lack of capacity to meet this need. The situation is far from hopeless, but meaningful improvement will require action on multiple fronts. The potential benefits for students and the nation are significant.

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1

Introduction

Engineering education is emerging as an important component of US K–12 education. Although not as prevalent as other, more established school subjects, engineering is increasingly finding its way into standards, instructional materials, and assessments. Across the country, students in classrooms and after- and out-of-school programs are participating in hands-on, problem-focused learning activities using the engineering design process. When done well, these experiences can be engaging, support learning in other areas, such as science and mathematics, and provide a window into the important role of engineering in society. For some students, experiencing engineering in K–12 may factor into decisions about college and career. From a broader policy perspective, exposing more K-12 students to engineering may help address concerns about the adequacy of the nation's STEM talent pool to meet the demands of today's global economy (e.g., NRC 2011).

Engineering can be presented to K–12 students in many different ways and with a variety of emphases. It can be a standalone subject, much as mathematics, history, or English language arts; a support to learning in other subjects, such as science; or a connector between multiple subjects, as is sometimes the case in STEM (science, technology, engineering, and mathematics) programs. This variability is partly a result of engineering's newness as a K–12 subject. It also reflects the fact that individuals and groups with different goals and perspectives have developed K–12 engineering materials.

As the landscape of K–12 engineering education continues to evolve, educators, administrators, and policymakers will need to consider the capacity of the US education system to meet current and anticipated needs for K–12 teachers of engineering. In examining this capacity concern, a number of related questions arise regarding exactly what such educators need to know and be able to do in order to be effective, and where and how they might develop such expertise.

A BRIEF BACKGROUND ON ENGINEERING IN K–12 EDUCATION

Efforts to introduce engineering to K–12 students can be traced back at least half a century. In the late 1960s, the Engineering Concepts Curriculum Project, funded by the National Science Foundation (NSF), published *The Man Made World—A Course on the Theories and Techniques That Contribute to Our Technological Civilization*, a high school engineering course that at its peak enrolled some 100,000 students (Liao 1997). The organization funded to do the work, the Commission on Engineering Education, explained the effort this way (NAE 1966, pp. 104–105):

> The course is intended for the normal college-bound student, not necessarily for the potential engineering or science major. It is our conviction that a well-organized introduction to engineering concepts should be one of the most desirable elements of the basic education of any well-informed citizen.

Although *The Man Made World* did not survive much beyond the end of NSF's support, the project's emphasis on general literacy, rather than narrow technical training, foreshadowed a goal of many similar initiatives that would emerge decades later.

For nearly 30 years after publication of *The Man-Made World*, there were few formal, organized efforts to introduce K-12 students to engineering ideas and practices. Then in the late 1990s, two developments brought engineering more into the mainstream of K–12 education. First, various groups began to develop K–12 curricula that included engineering.[1] Second, organizations and states began to write K–12 education standards that addressed engineering concepts and skills. The national *Standards for Technological Literacy: Content for the Study of Technology* were first published in 2000 by the International Technology Education Association (ITEA 2007),[2] and in 2001 Massachusetts established the first state science education standards (MDESE 2016). By the early 2010s, about three-quarters of states included engineering content in their K–12 curriculum frameworks for technology education, career and technology education, and/or science education (Carr et al. 2012).

In 2012 the National Research Council (NRC 2012a) published *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Both the *Framework* and the resulting *Next Generation Science Standards: For States, By States* (NGSS; NGSS Lead States 2013) include engineering concepts and practices alongside those for science, a significant departure from earlier versions of K–12 science standards[3] and a recognition of the role engineering can play in science teaching and learning. At the time this report went to press, 20 states and the District of Columbia had adopted NGSS, and 24 others had adapted the standards to fit state requirements (NSTA 2019). NGSS presents a major opportunity to advance US engineering education in the primary and secondary grades by integrating the subject with science.[4] Throughout the report, the committee draws attention to the potential role and learning needs of this key teacher population.

The recent growth of engineering in K–12 has not been limited to its integration with science as called for in the NGSS. According to the National Survey of Science and Mathematics Education (NSSME; Banilower et al. 2013, 2018), the number of standalone engineering courses, at least at the high school level, has also been growing (table 1-1), and K–12 schools at all levels have been expanding opportunities for students to take part in informal engineering education activities (table 1-2).

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[1] NAE and NRC (2009) reviews a number of these.

[2] In 2010, the ITEA changed its name to International Technology and Engineering Educators Association, ITEEA, reflecting the field's increasing shift toward engineering.

[3] In the 1990s, both the American Association for the Advancement of Science (AAAS) and the NRC developed national standards for K–12 science education. AAAS's *Benchmarks for Science Literacy* (AAAS 1993) devoted two chapters (chapter 3, The Nature of Technology, and chapter 8, The Designed World) to concepts related to technology and design. But although engineering was mentioned, almost none of the standards included it explicitly, and the standards did not suggest that science learning should be connected to engineering. The NRC's *National Science Education Standards* (NRC 1996) likewise devoted attention to the idea of technological design and mentioned in passing the role of engineering, but no standards specifically called it out, and the idea of the integration of engineering with science was not discussed.

[4] The idea of integrated forms of STEM teaching and learning is not new, and there are multiple ways integration can occur. Previous work by the National Academies of Sciences, Engineering, and Medicine found that many programs and projects that attempt STEM integration use some form of problem- or project-based learning, and these were often situated in an engineering design context (NAE and NRC 2014).

TABLE 1-1 Percent of US High Schools Offering at Least One Engineering Course, 2012 and 2018

	2012[a]	**2018**[b]	**Change**
Any level course	24%	46%	+92%
Noncollege preparatory course	14%	31%	+121%
First-year college preparatory, including honors	13%	29%	+123%
Second-year advanced	5%	17%	+240%

[a] Adapted with permission from Banilower et al. 2013. © 2013 Horizon Research.
[b] Adapted with permission from Banilower et al. 2018. © 2018 Horizon Research.
SOURCES: Banilower et al. (2013, 2018).

TABLE 1-2 Percent of US K–12 Schools with One or More Engineering-Focused Competitions or Clubs, 2012 and 2018

	Engineering Competitions			**Engineering Clubs**		
	2012[a]	**2018**[b]	**Change**	**2012**[a]	**2018**[b]	**Change**
Elementary	11%	24%	118%	7%	28%	+300%
Middle	19%	35%	84%	13%	36%	+177%
High	33%	47%	42%	21%	35%	+67%

[a] Adapted with permission from Banilower et al. (2013). © 2013 Horizon Research.
[b] Adapted with permission from Banilower et al. (2018). © 2018 Horizon Research.
SOURCES: Banilower et al. (2013, 2018).

The rising prevalence of engineering in K–12 can also be seen in the results of a new national Technology and Engineering Literacy (TEL) assessment, administered to large samples of eighth-grade students as part of the National Assessment of Educational Progress (NAEP).[5] In 2018, 25 percent of students reported that they had taken or were currently taking a class in engineering, up from 19 percent who did so in 2014, the first year the assessment was administered (NCES 2014, 2018).

The expansion of engineering opportunities in K–12 education has recently gained support among an important group of engineering educators at the postsecondary level. More than 100 deans of engineering schools have agreed (UMd 2018) to grant some form of college credit to students who successfully complete an advanced engineering course in high school (NSF 2018). NSF-funded researchers are pilot testing a possible curriculum for such a course and, depending on the pilot's results, the College Board, which oversees the Advanced Placement (AP) program, may add engineering to its portfolio of AP offerings (personal communication, L. Abts, University of Maryland, 1/2/18).[6]

Making engineering education available to US K–12 students is more than a question of providing advanced classes for a select group of high school students. In its conceptual

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[5] Information about the assessment and results is available at https://nces.ed.gov/nationsreportcard/tel/.
[6] At least one extant high school engineering course, *Engineer Your World: Engineering Design and Analysis*, offered as a dual-enrollment option at the Cockrell School of Engineering, University of Texas, Austin. This course, also developed with funding from the National Science Foundation, provides students the opportunity to earn college credit that counts as core science credit for nonengineering majors and as elective credit for engineering majors (personal communication, C. Farmer, University of Texas, Austin, 9/23/19).

framework guiding the development of the NAEP TEL assessment, the National Assessment Governing Board (NAGB) of the US Department of Education makes the following case for why all US students should know more about technology and engineering (NAGB 2018, p. 2):

> Because technology is such a crucial component of modern society, it is important that students develop an understanding of its range of features and applications, the design process that engineers use to develop new technological devices, the trade-offs that must be balanced in making decisions about the use of technology, and the way that technology shapes society and society shapes technology. Indeed, some have argued that it is time for technology and engineering literacy to take its place alongside the traditional literacies in reading, mathematics, and science as a set of knowledge and skills that students are expected to develop during their years in school.

Efforts to put engineering literacy on par with literacy in reading, mathematics, and science represent an ambitious objective that begs the question of how best to prepare and support educators who will be tasked with teaching engineering, whether as a standalone course, as a companion to one or more other STEM subjects, or in an out-of-school setting. Meeting the objective will involve addressing issues of equity and inclusion, an especially relevant challenge given the longstanding lack of diversity within postsecondary engineering education and the engineering workforce.

STATEMENT OF TASK

To address the question of what will be required to prepare and support future teachers of engineering, the National Academy of Engineering and the Board on Science Education of the National Academies of Sciences, Engineering, and Medicine (the National Academies), with support from NSF, convened an expert committee to conduct extensive data gathering and analysis. The 16-member Committee on Educator Capacity Building in K–12 Engineering Education included K–12 educators with experience teaching engineering in the classroom and in out-of-classroom settings at both the elementary and secondary levels, as well as experts in pre- and in-service teacher education, science education, and engineering. Biographical information for the committee members is in appendix A. The statement of task for the committee is shown in box 1-1.

BOX 1-1 Statement of Task

An ad hoc committee under the auspices of the National Academy of Engineering (NAE), in collaboration with the National Research Council Board on Science Education, will oversee a project to understand current and anticipated future needs for engineering-literate K–12 educators in the United States and how these needs might be addressed. In meeting this goal, the committee will answer questions in three areas:

<u>The Preparation of K–12 Teachers of Engineering</u>

- What is known from education and learning sciences research about effective preparation of K–12 educators to teach about engineering?
- What appear to be the most promising educator-preparation practices currently in use?

- What additional research is needed to improve and expand effective approaches for preparing K–12 teachers of engineering?

<u>Professional Pathways for K–12 Teachers of Engineering</u>

- What formal (e.g., state certification) and informal (e.g., "badging") mechanisms are being used to recognize expertise and support career pathway options for K–12 teachers of engineering?
- What formal and informal credentialing mechanisms from domains other than education might be adapted or adopted to recognize expertise and support career pathway options for K–12 teachers of engineering?
- What are the practical and policy impediments to instituting effective credentialing for K–12 teachers of engineering, and how they might be addressed?

<u>The Role of Higher Education</u>

- What roles do or might postsecondary institutions, including but not limited to four-year engineering and engineering technology programs, play in the preparation of K–12 teachers of engineering?
- What are the practical and policy impediments to involving higher education in the preparation of K–12 teachers of engineering, and how might they be addressed?

The original statement of task used the term "engineering educators" to describe what the report now calls "teachers of engineering." The word "educator" was used initially because it allowed the committee to refer to both classroom teachers and educators (who may not formally be teachers) working in informal settings. However, as noted later in this chapter, very little of the report deals with informal education. In addition, on reflection, the committee realized that "engineering educator" suggests that there exists a professional whose job it is to teach engineering and solely engineering. In fact, as the rest of the report discusses, this situation, while true in some cases, is not so in most circumstances. For example, some science teachers also teach engineering, as do some mathematics and technology educators, and elementary teachers are responsible for teaching multiple subjects. As far as we can tell, relatively few K–12 teachers teach only engineering. Thus the term "teachers of engineering" provides the nuanced meaning needed to accommodate the evolving nature of this new component of K–12 education and is used throughout the report. It refers to any elementary or subject-matter secondary teacher who spends some portion of the school day providing engineering instruction.

In meeting the statement of task, the committee will (1) conduct an in-depth review of the literature related to preparation of K–12 teachers of engineering and (2) inventory US preservice and in-service programs that support the preparation and professional development of K–12 teachers of engineering. The inventory will describe the nature (e.g., curriculum) and history of the programs and, if known, the number of educators reached and the evidence for impact (e.g., on individual teaching practice and the growth of K–12 engineering education locally, regionally, or nationally).

The committee's final report will propose steps key stakeholders might take to increase the number, skill level, and confidence of K–12 teachers of engineering in the United States. Stakeholders will include professional development providers, postsecondary preservice education programs, postsecondary engineering and engineering technology programs, formal and informal educator credentialing organizations, and the education and learning sciences research communities.

ADDRESSING THE STATEMENT OF TASK

In addressing its statement of task, the committee considered educator needs in two dimensions, one related to the individual and the other related to the education system as a whole. In the first case, the committee addressed the skills and knowledge that K–12 teachers of engineering require to be competent and confident, and how and where they might obtain these competencies. In the second, the committee focused on the programs and policies that facilitate the development of such skills and knowledge, including teacher preparation and professional development.

The statement of task does not distinguish among the different subgroups of teachers that comprise the workforce of K–12 teachers of engineering. Yet we know that not all teachers face the same demands or require the same types of support to provide effective instruction. Thus when the data allow, we consider separately the different engineering-related learning needs of teachers at the elementary and secondary levels. Similarly, when appropriate, we highlight how the preparation of certain subject-matter specialists, such as science teachers, to teach engineering might differ from that of others, such as technology teachers.[7]

The original statement of task called on the committee to consider not only kindergarten but also pre-K education. While the committee recognizes the importance of exploring ways to expand engineering education strategically and systematically to the pre-K level, the research base around engineering education at this level is insufficiently robust to support evidence-based findings, conclusions, and recommendations. More generally, there is no consensus in the education research community about who should be counted as a pre-K educator or what their credentials should be. Researchers also do not agree about what kinds of educational experiences constitute pre-K learning environments. For all of these reasons, the committee decided to focus this report only on the preparation of teachers of engineering for grades K–12.

Although informal education is not mentioned in the statement of task, the committee recognizes that this is a large and important component of the education system and discussed it often during the project. Museums, science and technology centers, aquaria, and botanical gardens are among the many types of institutions that provide visitors—adults and children—with learning opportunities in STEM. Other components of the informal education sector include the growing Maker movement, university- and industry-sponsored STEM programs and outreach, initiatives of professional STEM organizations, and STEM-focused competitions.

There are several important differences between formal and informal education relevant to this project. A provider of informal learning opportunities in engineering needs someone to deliver the programming, but that person may or may not have experience as a K–12 educator and may or may not possess knowledge of engineering. As a result, the professional learning one might recommend for or expect of an informal educator may be quite different than for a classroom teacher. Another difference is that participants in informal education programs may themselves be K–12 classroom teachers. Informal settings thus provide a potential pathway for teachers to build content and process knowledge of engineering, often in a low-stakes setting.

[7] For a description and brief history of the field of technology education, see box 4-1.

This means that informal educators need to be seen both as needing professional learning support and providing such support to others (e.g., classroom teachers).

The committee took these complexities and uncertainties into account, along with the sparse research literature associated with educator professional learning in informal settings, in deciding to treat informal education in a very limited way in this report. The committee emphasizes that its decision does not reflect a lack of appreciation of the hundreds of popular informal STEM-focused programs.

THE BASIS FOR EVIDENCE USED IN THE REPORT[8]

The committee discovered that there is relatively little evidence about various components of effective engineering education at the K-12 level. Much of what is known in the field of STEM teacher preparation relies heavily on scholarship about teaching generally and about teaching science, so the committee drew from a number of related areas of evidence. The kinds and levels of evidence available to the committee influenced how it addressed the statement of task and informed its ability to draw conclusions and make recommendations.

As noted in the statement of task, the committee was asked to undertake a survey of the literature to elucidate existing policies around certification and credentialing, the roles of higher education in preparing teachers of engineering, and associated policy levers and impediments. The committee also was tasked with examining and reporting on evidence of best practices and needs for additional research in the preparation of teachers of engineering.

Many NASEM study committees that have addressed issues in education have had to decide what constitutes appropriate levels of evidence for their work. While a detailed overview of what constitutes appropriate evidence in education research is beyond the scope of this report, readers who seek additional details can find them in NRC (2010, 2012b) and NASEM (2015, 2017).

In its data collection and analysis, the committee recognized three general categories of research (see, e.g., NRC 2002):

- **Descriptive** research describes facts or processes without inferring any underlying basis for them. For example, this report describes the characteristics and approaches of multiple local and national programs to prepare K–12 teachers of engineering for both formal and informal settings. Nearly all of the data reviewed by the committee were descriptive in nature.
- **Causal** research seeks to discover whether a specific intervention leads to a specific response and attempts to distinguish causation from noncausal relationships with other factors (correlation).
- **Mechanistic** research aims to understand why some causal factor or combination of factors leads to an observed effect.

None of these approaches is necessarily simple or straightforward. For example, while many researchers consider description to be the most basic approach to collecting evidence and posing subsequent research questions, descriptive work involves a range of methodologies, ranging from ethnography to field studies to design based implementation work. Such research plays an

[8] In addition to the cited sources, some of the text in this section is adapted from NASEM (2017, pp. 25–27).

essential role in both building theory and interventions, as well as exploring mechanisms and examining the role of contexts.

Establishing a causal relationship between an experimental intervention and outcome can be extremely difficult and such claims serve as the basis for debate and replication of experiments among researchers. Examining differences between comparable research subjects (e.g., people, approaches to professional development, or organizations) may allow for causal claims.

In evaluating the research on claims for successful approaches to professional development and preservice education for current and future teachers of engineering, the committee looked for high-quality research across these traditions—descriptive, causal, and mechanistic—since all rigorous empirical work is worth examining. The committee, staff, and external consultants were able to identify only a small number of quasi-experimental studies. More studies involved qualitative and interpretive research that drew on data from interviews, observations, self-reports from the study subjects, and surveys. To the extent possible, the committee limited the research it drew upon to peer-reviewed studies in which research methods were explained in ways that would allow for replication of the study.

STUDY PROCESS

The committee held five in-person meetings, two of which were combined with information-gathering workshops, and three conference calls. (Workshop agendas are provided in appendix B.)

The committee commissioned supplementary research to bolster its understanding of the preparation of K–12 teachers of engineering. The Education Development Center (EDC) performed a landscape scan of professional development opportunities for teachers of engineering, and EDC researchers presented their findings to the committee in multiple meetings. Researchers at the Urban Institute examined, and provided the committee with information from, the federal School and Staffing Survey. Scholars from Texas A&M University analyzed state teacher credentialing policies related to engineering.

With assistance from the Academies' Research Center, project staff conducted a literature review of all available research from the past 20 years on K-12 engineering education. Staff also considered literatures from teacher education, science education, and general engineering education, as these fields offer the best insight into the desirable outcomes outlined in the statement of task. The databases used in the search were ERIC (Ovid), IEEE, ProQuest Research Library, Scopus, and Web of Science.

Following its information-gathering meetings and the literature search, the committee conducted its work in closed sessions to analyze the available evidence in order to formulate conclusions and recommendations.

AUDIENCES

The committee expects that this report will be important to a number of audiences. They include but are not limited to:

- Federal agencies that support the professional development and preservice learning of K–12 STEM educators
- Federal executive branch offices with a role in setting K–12 STEM education policy

- Individual members of Congress, their staff, and congressional committees engaged in K–12 STEM education issues
- State, district, and local government leaders involved in K–12 and postsecondary STEM education
- Offices of state governors
- Organizations representing K–12 STEM teachers
- STEM professional associations with an interest in K–12 STEM education
- Organizations that promote increased participation of underrepresented populations in STEM education and careers
- Informal education groups, such as libraries, makerspaces, museums, science and technology centers, aquaria, and botanical gardens
- Higher education institutions involved in preparing future engineers and prospective K-12 teachers
- Providers of professional development for K–12 STEM educators
- Members of school boards, and school and district leaders who play critical roles in the health of education systems at various levels
- Education researchers and research centers with an interest in K–12 engineering education
- Business and industry associations with an interest in K–12 STEM education
- Foundations that support K–12 STEM education initiatives

REPORT ORGANIZATION

Chapter 2 outlines the key concepts, practices, and habits of mind in engineering, and compares these with how science frames similar issues. Chapter 3 addresses goals that the committee sees as drivers for K–12 engineering education. Chapter 4 presents data on the K–12 engineering education workforce and the status of teacher preparation and professional development in this domain. Chapter 5 summarizes what is known from research about the professional learning needs of K–12 educators generally and teachers of engineering specifically, as well as what is known about opportunities to meet these needs. Chapter 6 discusses elements of the larger US education system that shape the preparation and on-going learning of K–12 teachers of engineering. Chapter 7 presents the committee's conclusions and recommendations.

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2

Engineering and K–12 Education

This chapter provides an overview of the essential elements of engineering; describes the important connections between engineering and the other three STEM subjects—science, technology, and mathematics; and reviews the different learning objectives for K–12 engineering. This background should be helpful to readers unfamiliar either with engineering or with engineering in K–12 settings.

WHAT IS ENGINEERING?

Engineering is both a knowledge of the creation and design of human-made products and processes and a problem-solving method called design under constraint.[1] One such constraint is the laws of nature, such as the conservation of mass and energy, which are discoverable by science. Engineering cannot accomplish something that violates these laws. Other constraints include money, time, ergonomics, available materials, manufacturability, environmental regulations, and reparability. In addressing design challenges, engineering uses technological tools as well as concepts and practices from mathematics and science.

In this section we provide an overview of three critical aspects of engineering: its essential qualities, the design process, and core concepts.

Essential Qualities of Engineering

Engineering exhibits a number of essential qualities (box 2-1) that help define the discipline and are shared with many other human endeavors.

BOX 2-1
Essential Qualities of Engineering

- Systematic
- Purposeful
- Iterative
- Embraces failure
- Depends on teamwork
- Quintessentially human
- Inherently creative and optimistic
- Attentive to social and ethical concerns

Adapted from NAE and NRC (2009), pp. 151–152.

Foremost among engineering's essential qualities is that it is systematic and purposeful. The process of engineering design, described in the next section, is a *systematic* way of identifying needs, wants, and/or problems and then devising solutions to address them. The targets of

[1]This definition is based on box 1-1 in NAE and NRC (2014).

engineering problem-solving include complex, global-scale issues,[2] such as providing access to clean water, as well as simple, everyday concerns, like controlling stoplights at a busy intersection. Engineering should not be confused with tinkering, a loosely structured process of trial and error that typically is not grounded in careful analysis or data collection.

Engineering is *purposeful* in that it is driven by explicit goals. This does not mean, however, that engineering problems have only one solution. In fact, engineering accommodates, emphasizes, and embraces multiple solutions, as long as they all satisfy the requirements and constraints set out at the beginning of the journey.

The journey of engineering is an *iterative* process involving repeated cycles of testing, data collection, analysis, and improvement to reach an optimal solution (the destination). This iterative approach to problem solving is necessary because early versions of a solution almost always fail to achieve the desired goal. It is much better for such failure to occur before a technology is introduced in the real world, while it can be addressed through improvements in the design. Engineering therefore *embraces failure* as an important and necessary element of technology development (Petroski 1992).

Modern engineering *depends on teamwork*. It relies on large, diverse, and often geographically dispersed groups of individuals. Most contemporary engineering challenges (e.g., NAE 2016) can be addressed only by combining expertise from multiple subdisciplines (e.g., mechanical, electrical, civil, and environmental) as well as the physical and life sciences, applied mathematics, and the humanities and social sciences. Turning an engineering solution into a commercially viable product requires even more diverse expertise, in areas such as marketing, finance, and patent and environmental law. Experts increasingly see this convergence among multiple fields to address important, complex societal challenges as a necessary condition for success in engineering research (NASEM 2017).

Engineering is *creative*, in the sense of being generative as well as involving imagination and flexible thinking, and *inherently optimistic*, in that it treats every problem as potentially solvable and every need as addressable (subject to the kinds of constraints described below). And although humans are not the only species capable of solving problems, the ability *to engineer is quintessentially human*. For all of recorded history, people have created and used tools to meet their needs and wants, using many of the techniques codified in modern engineering: identifying problems and building, testing, and refining solutions to them.

Finally, engineering is *attentive to social and ethical concerns*, for the simple reason that technology has positive and negative impacts on people, society, and the planet (e.g., NAE and NRC 2002). When designing a solution, engineers must take into account the needs and concerns of the populations to be served. This ensures that the culture and values of the end users inform technology development. Otherwise, even effective “solutions” may not be accepted or implemented.

The ethical dimension of engineering is relevant in the professional behavior of engineers as well as societal concerns about technological development. Like physicians following the Hippocratic Oath, engineers follow codes of practice to ensure public safety, which is one of the reasons there are large margins of safety in engineered products and systems. More broadly, the ethical obligations of the engineer call for consideration of both those whom technology will benefit and those it may potentially harm. These obligations must account for the possibility that some benefits and harms may have been unanticipated in the original design. Ethical concerns

[2] One framing of such issues is the National Academy of Engineering’s Grand Challenges for Engineering (engineeringchallenges.org).

arise in areas such as big data, climate change, emerging technologies such as synthetic biology and artificial intelligence, human-enhancement technologies, military technology, and sustainability.

Engineering Design

Engineering design is the problem-solving process used by engineers (box 2-2).

BOX 2-2
Engineering Design

Engineering design is a process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances.

SOURCE: ABET (2018). Reprinted with permission. This text is the sole property of ABET, Inc. and is protected by US and international copyright laws.

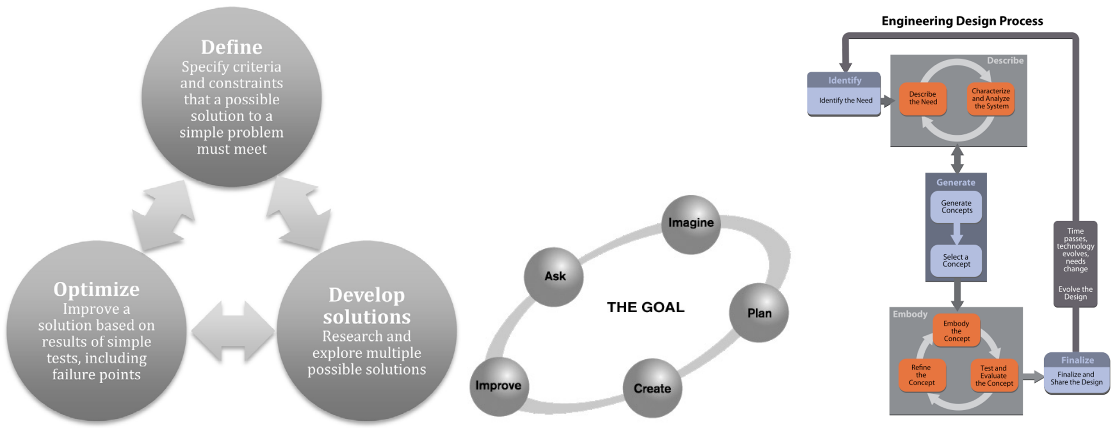
While the engineering design process always aims to address human wants and needs, there is no single model for describing it. Models vary in detail and structure, but all consist of a similar set of distinct steps (box 2-3).

BOX 2-3
Typical Steps in the Engineering Design Process

- Identify the problem or need
- Research what others have done to solve similar problems
- Generate concepts for possible solutions
- Select a concept for testing
- Construct and test a prototype
- Collect and analyze performance data
- Redesign/improve the solution
- Communicate the solution

Importantly, these steps rarely if ever occur in a linear fashion from start to finish. One might expect that the step of problem identification always comes first. However, other steps in the process, such as prototype development and testing, can lead engineers to discover information that changes the very nature of the problem to be solved. Revisiting the initial design based on data from testing likewise might change thinking about which of the generated concepts is optimal. In addition, as noted in the earlier discussion on iteration, there can be many cycles of redesign and testing before engineers determine that a solution is acceptable. The nonlinear nature of engineering design is evident in the example models shown in figure 2-1.

FIGURE 2-1 Example Models of the Engineering Design Process



SOURCES: (Left to right) NGSS Lead States (2013, volume 2, appendix I), EiE (2019), Guerra et al. (2012). Reprinted with permission by the Museum of Science, Boston and the EiE® team.

Core Engineering Concepts

The engineering design process encompasses a number of core concepts, skills, and habits of mind.[3] For example, in framing a problem engineers must understand the design *requirements*—the physical and functional needs that the design must satisfy—and use these to develop detailed *specifications* against which the success of the design will be measured. Equally important are the *constraints* within which the engineer must work; these may include available materials, time, money, and economical, legal, political, social, ethical, and aesthetic limitations inherent to or imposed on the design.

To select the best solution from among a number of competing alternatives, engineers engage in a process called *optimization*. When competing design requirements make it very difficult to select the most appropriate solution, engineers must decide to prioritize (and optimize) one attribute over another, a process of *trade-off*. A simple example might involve choosing to optimize low weight over cost savings in the design of an airplane wing, which might necessitate the use of lighter but more expensive materials.

Once a design enters the build-test-redesign (or create-improve) phase, engineers may use *modeling*—and must perform *analysis*—to evaluate and refine their solution. Modeling involves representing the essential features of processes or systems that facilitate engineering design and can contain graphical, physical, or mathematical representations. Analysis, typically involving data collection of some kind, is a systematic and detailed review that can inform design decisions, define or clarify problems, predict or assess performance, evaluate alternatives, determine economic feasibility, and/or investigate failures. Returning to the airplane case, engineers might use modeling software to simulate the effects of fast-moving air on the stability of one of the wing's flaps, analyzing data from dozens of simulations of different flap configurations to determine which is most likely to behave reliably in flight. The chosen design

[3] A more detailed explication of these ideas appears in NAE and NRC (2009, pp. 82–92).

might then be further modeled with a physical prototype, whose performance could be tested in a wind tunnel.

A final key idea in the engineering design process, and a central focus for engineering more broadly, is *systems*. A system is any organized collection of discrete elements (e.g., parts, processes, people) that work together in interdependent ways to fulfill one or more functions. To be effective designers, engineers must have a good grasp of how systems work and the factors that influence their performance.

Diversity in Engineering

No discussion of engineering would be complete without mentioning the field's diversity challenge. Degree earning and employment in engineering are characterized by very limited gender, ethnic, and racial diversity (table 2-1). White and Asian males earn the vast majority of undergraduate degrees and hold the bulk of faculty positions in the field, and they hold the lion's share of jobs in engineering. Women African Americans, American Indians/Alaska Natives, and Hispanics of any race are significantly underrepresented in engineering education and occupations.

TABLE 2-1 Race/Ethnicity and Gender in Engineering Education and Occupations Compared with the US Population, Various Years

	White	Hispanic	African American	Asian	American Indians/Alaska Natives	Female
Tenured/tenure-track engineering faculty[a]	55.9	3.8	2.4	28.3	n/a	17.4
4-year engineering degree recipients[b]	61.5	9.6	3.8	10.9	0.3	19.8
Employed in engineering occupations[c]	69.2	8.3	3.6	16.3	0.2[d]	15.6
US population[e]	76.5	18.3	13.4	5.9	1.3	50.8

[a] Tenured/tenure-track faculty comprise full, associate, and assistant professors. Data for 2018 from Engineering by the Numbers (Roy 2019) and are based on a survey of 4-year, ABET-accredited institutions that awarded at least one degree that year.
[b] Calculations from the 2014 Integrated Postsecondary Education Data System; population of institutions from the NCES (NAE 2017, table 3-6).
[c] Data from the 2017 National Survey of College Graduates (NSF 2019, table 9-7).
[d] Includes males only; data for females suppressed by NSF for confidentiality reasons.
[e] Estimates for 2018 from US Census Bureau (2018).

The relevance of diversity to the preparation and support of K-12 teachers of engineering will be discussed later in the report. Here the committee notes the value of diversity to the engineering design process, the subject of the preceding two sections, and to assuring all citizens have opportunity to pursue an engineering career, a matter of social justice. Regarding the first point, research (e.g., Chubin et al. 2005; Corbett and Hill 2015; Emerson 2014; NAE 2002; Phillips 2014) finds that a more diverse workforce is more creative and innovative than a homogeneous one. Given the critical role of engineering design and teamwork to engineering problem-solving, it may be, as suggested by former NAE president Wm. Wulf, that without diversity "we limit the set of life experiences that are applied, and as a result, we pay an opportunity cost—a cost in products not built, in designs not considered, in constraints not understood, in processes not invented" (Wulf 1998, p. 9). Regarding the second, the abilities gained during an engineering education are versatile and relevant to a variety of occupations and fields, which helps explain the higher median lifetime earnings (NAE 2018, pp. 42-47) and lower unemployment rates (NAE 2018, pp. 47-48) of those with engineering degrees compared with those with other STEM and non-STEM degrees. For a variety of reasons, earnings are significantly lower for women and, especially, underrepresented groups who hold a BS engineering degree, compared with those for Whites (Carnevale et al. 2011). Even taking this into account, an engineering degree offers significant socioeconomic benefits.

ENGINEERING'S RELATIONSHIP TO SCIENCE, TECHNOLOGY, AND MATHEMATICS

Engineering, science, and mathematics are interdependent disciplines, and advances in one often enable progress in another. For example, the basic scientific understanding of DNA's structure and the discovery of chemical methods of decoding strands of genetic material led engineers to create genome-sequencing machines that generated massive amounts of data whose analysis required algorithms developed by mathematicians (Talesnik 2015). Gene sequencing led in turn to additional scientific discoveries and the potential for a new generation of computers that use principles of information storage in DNA (e.g., Extance 2016; Service 2017).

Although not strictly defined as a discipline, technology encompasses the entire system of knowledge, processes, devices, people, and organizations involved in the creation and operation of technological artifacts, as well as the artifacts themselves.[4] In the example above, the process of decoding genetic information and the machines developed to do this work are technologies. Much of modern technology is a product of engineering, science, and mathematics, and people in all three fields use technological tools.

Science shares many of the essential characteristics of engineering described earlier in this chapter. Like engineering, science is a creative, systematic, and purposeful endeavor that pays heed to social and ethical concerns. Science develops models and theories to explain and predict phenomena. Like engineering, this process occurs through recursive and iterative testing and refinement. Failure of a model- or theory-based prediction is an expected step that points the direction for needed improvement of the model or theory, just as failure of a design prototype provides information that guides improvement of an engineering solution. While science seeks to eventually find a singular best theory to explain and predict phenomena in a particular domain, multiple competing ideas can coexist when there is no evidence that differentiates between them.

While engineering and science share many qualities, the disciplines also exhibit differences. The *Framework for K–12 Science Education* (NRC 2012), for example, highlights eight practices that underlie the work of both engineers and scientists while pointing out that three of them—developing and using models, planning and carrying out investigations, and analyzing and interpreting data—play out differently in the two disciplines (table 2-2).

[4] This definition of technology is based on box 1-1 in NAE and NRC (2014).

TABLE 2-2 Notable Differences in the Shared Practices of Engineering and Science

Engineering	**Science**
Asking questions and defining problems	
Science begins with a question about a phenomenon and seeks to develop theories that can provide explanatory answers to such questions. A basic practice of the scientist is formulating empirically answerable questions about phenomena, establishing what is already known, and determining what questions have yet to be satisfactorily answered.	Engineering begins with a problem, need, or desire that suggests an engineering problem that needs to be solved. Engineers ask questions to define the engineering problem, determine criteria for a successful solution, and identify constraints.
Developing and using models	
Engineering uses models and simulations to analyze flaws, strengths, and limitations in existing and proposed new systems.	Science uses models and simulations to develop explanations about natural phenomena.
Planning and carrying out investigations	
Engineers use investigations both to gain data essential for specifying design criteria or parameters and to test their designs.	Scientists use investigations to test existing theories and explanations or to revise and develop new ones.
Analyzing and interpreting data	
Engineers analyze data collected in the tests of their designs and investigations; this allows them to compare different solutions and determine how well each one meets specific design criteria. Engineers use a variety of tools to identify major patterns and interpret the results.	Scientific investigations produce data that must be analyzed in order to derive meaning and to identify significant patterns and features in the data.
Constructing explanations and designing solutions	
The goal of science is the construction of theories that can provide explanatory accounts of features of the world. Scientific explanations are explicit applications of theory to a specific situation or phenomenon, perhaps with the intermediary of a theory-based model for the system under study.	The goal of engineering is to design solutions to engineering problems using scientific knowledge and models of the material world. There is usually no single best solution but rather a range of solutions. Which one is the optimal choice depends on the criteria used for making evaluations.

Adapted from NRC (2012), box 3-2.

LEARNING OBJECTIVES FOR K–12 ENGINEERING EDUCATION

The preceding sections reviewed key concepts and practices of engineering and suggested how engineering relates to the other three STEM subjects. With that background, we now consider how researchers and practitioners have translated these ideas into learning objectives for K–12 students. Learning objectives prioritize and organize a discipline's content in a way that makes clear what students are expected to know and be able to do as a result of their educational experiences. Many times, learning objectives are presented in the form of curriculum standards.

K–12 engineering education efforts generally situate engineering among STEM subjects in one of two ways: engineering in the foreground, with science, mathematics, or both subjects in a supporting role; or science or mathematics, or both, in the foreground, with engineering in a supporting role. As might be expected, the line between these two perspectives is often blurry.

In the first case, science and mathematics serve engineering, with the primary goal of improving understanding of engineering and the quality of engineering design solutions. Students may apply scientific knowledge or engage in scientific experimentation—gathering, analyzing, and interpreting data—in order to better understand the design challenge and potential solutions. The focus, which is prevalent in standalone engineering courses or programs, is on using science and mathematics as tools of engineering.

In the second case, engineering serves science and mathematics, with the primary goal of improving student understanding of science and mathematics concepts and practices. This is a prevalent approach in many K–12 engineering education programs. In the committee's survey of teacher preparation and professional development in engineering, for example, 70 percent of respondents indicated that one of their top three program goals was to improve science instruction, and 38 percent indicated a top goal was to improve mathematics instruction. The focus in this case is less on building student understanding of engineering than on enhancing student interest, motivation, and learning of science and/or mathematics.

Although the two framings of K–12 engineering education share characteristics, their different emphases can lead to different learning objectives for students and, by implication, their teachers. The next two sections present examples of both framings.

Science and Mathematics in the Service of Engineering

One high-level conception of the engineering knowledge and skills that K–12 students should acquire is presented by Moore and colleagues (2014, 2015), who developed a framework for "quality in engineering education" (table 2-3).The framework developers started with the student outcomes criteria developed by ABET to accredit undergraduate engineering programs.[5] Using a design research methodology, Moore and colleagues initially compared the ABET criteria to Massachusetts state standards for K–12 science and technology/engineering education (MDOE 2006)[6] to identify potential omissions or content inappropriate for K-12 students. A second iteration compared the evolving set of indicators to a larger group of state K–12 engineering standards. Altogether, the document underwent six cycles of revision, involving a mix of expert evaluations and comparisons with other presentations of K–12 engineering knowledge, skills, and habits of mind.

TABLE 2-3 Framework for Quality K–12 Engineering Education

[5] A 2017 revision of the ABET document (ABET 2017) combined and reworked the language of portions of the previous version's 13 student outcomes.
[6] Massachusetts published a revised version of these standards in 2016 (MDESE 2016).

		Key Indicator	Description
Central Aspects of Engineering		**Processes of Design (POD)**	Design processes are at the center of engineering practice. Solving engineering problems is an iterative process involving preparing, planning and evaluating the solution. Students should understand design by participating in each of the sub-indicators (POD-PB, POD-PI, POD-TE) below.
	POD Sub-indicators	**Problem and Background (PB)**	Identification or formulation of engineering problems and research and learning activities necessary to gain background knowledge.
		Plan and Implement (PI)	Brainstorming, developing multiple solutions, judging the relative importance of constraints and the creation of a prototype, model or other product.
		Test and Evaluate (TE)	Generating testable hypotheses and designing experiments to gather data that should be used to evaluate the prototype or solution, and to use this feedback in redesign.
		Apply Science, Engineering, Mathematics Knowledge (SEM)	The practice of engineering requires the application of science, mathematics, and engineering knowledge and engineering education at the K-12 level should emphasize this interdisciplinary nature.
		Engineering Thinking (EThink)	Students should be independent and reflective thinkers capable of seeking out new knowledge and learning from failure when problems arise.
Understand Engineering		**Conceptions of Engineers and Engineering (CEE)**	K-12 students not only need to participate in an engineering process, but understand what an engineer does.
		Engineering Tools, Techniques, and Processes (ETool)	Students studying engineering need to become familiar and proficient in the processes, techniques, skills, and tools engineers use in their work.
Professional Skills		**Issues, Solutions, and Impacts (ISI)**	To solve complex and multidisciplinary problems, students need to be able to understand the impact of their solutions on current issues and vice versa.
		Ethics (Ethics)	Students should consider ethical situations inherent in the practice of engineering.
		Teamwork (Team)	In K-12 engineering education, it is important to develop students' abilities to participate as a contributing team member.
		Communication Related to Eng (Comm-Engr)	Communication is the ability of a student to effectively take in information and to relay understandings to others in an engineering context.

SOURCE: Adapted with permission from Moore et al. (2015), figure 1.

The framework considers the application of mathematics and science knowledge to be of central importance, but the document's clear emphasis is on engineering. However, because the framework is very general, it is not directly usable as a guide to curriculum developers or providers of professional learning experiences for educators.

By comparison, the *Standards for Technological Literacy: Content for the Study of Technology (STL)*, developed by the International Technology and Engineering Educators Association[7] (ITEEA 2007),[8] is a much more detailed effort to describe learning objectives for K–12 engineering. ITEEA developed *STL* with the help of advisory committees appointed by the National Research Council (NRC 1999) and National Academy of Engineering and received comment on various drafts from hundreds of reviewers, including teachers working at field test sites in schools around the country.

The *STL*, which are widely used by the technology education community, address engineering in three ways: what students should know about the attributes of design, what they should know about the engineering design process, and the abilities that students should have related to the design process. For illustrative purposes, we present the learning objectives associated with this third standard, Standard 11, in table 2-4.

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[7] In 2010, the organization changed its name from the International Technology Education Association to ITEEA, reflecting the field's turn toward engineering education.

[8] ITEA first published its standards in 2000 and has published two minor updates since then.

TABLE 2-4 Grade-Band Benchmarks for *STL* Standard 11: Students Will Develop Abilities to Apply the Design Process

K–2 Grade Band	3–5 Grade Band	6–8 Grade Band	9–12 Grade Band
• Brainstorm people's needs and wants and pick some problems that can be solved through the design process. • Build or construct an object using the design process. • Investigate how things are made and how they can be improved.	• Identify and collect information about everyday problems that can be solved by technology, and generate ideas and requirements for solving a problem. • Present some possible design solutions in visual form and then select the best solution(s) from many. • Test and evaluate the solutions for the design problem. • Improve the design solution.	• Apply a design process to solve problems in and beyond the laboratory-classroom. • Specify criteria and constraints for the design. • Make two-dimensional and three-dimensional representations of the designed solution. • Test and evaluate the design in relation to preestablished requirements, such as criteria and constraints, and refine as needed. • Make a product or system and document the solution.	• Identify the design problem to solve and decide whether or not to address it. • Identify criteria and constraints and determine how they will affect the design process. • Refine a design by using prototypes and modeling to ensure the quality, efficiency, and productivity of the final product. • Evaluate the design solution using conceptual, physical, and mathematical models at various intervals of the design process to check for proper design and to note where improvements are needed. • Develop and produce a product or system using a design process. • Evaluate final solutions and communicate observation, processes, and results of the entire design process, using verbal, graphic, quantitative, virtual, and written means, in addition to three-

			dimensional models.

SOURCE: ITEA (2007). Permission granted by ITEEA. www.iteea.org.

In effect, *STL* Standard 11 attempts to operationalize learning associated with key elements of engineering design (box 2-2 and figure 2-1). One feature of *STL*, not present in Moore et al. (2015), is the separation of learning objectives into grade bands. This aspect reflects the idea that student learning should build from grade to grade over a student's school career. Considerable evidence points to the fact that depth of knowledge and reasoning ability can build over the course of one's education, in children as well as adults (NASEM 2018).

While work to delineate learning outcomes in K–12 engineering, like Moore et al. (2015) and *STL*, have acknowledged the importance of connecting engineering design to appropriate content in science and mathematics, few efforts have been made to specify the concepts from these two STEM domains with which students should be familiar. In part, this is because every engineering design challenge makes unique demands on students' science and mathematics knowledge. Some problems may require little or no application of ideas from these disciplines, while others may demand significant conceptual understanding as well as ability to apply the concepts. Even within a particular design challenge scenario, there is likely to be considerable variation in expectations based on a student's age or grade, prior coursework, and (as applicable) career and college goals.

Grubbs and colleagues (2018) have proposed specific science and mathematics learning objectives in different areas of engineering for high school students, using sources such as a taxonomy of fields and subfields developed for a review of STEM doctoral programs[9] and elements of the Fundamentals of Engineering exam (NCEES 2017). Their proposed taxonomic structure calls out science and mathematics core and subconcepts relevant to mechanical, civil, electrical, and chemical engineering. The researchers have begun to consider what learning progressions in these content areas might look like (Huffman et al. 2018). (This research is discussed more fully in Chapter 5, Science and Mathematics for Engineering.)

Engineering in the Service of Science and Mathematics

As noted in chapter 1, the Next Generation Science Standards (NGSS; NGSS Lead States 2013) present a new vision for K–12 science education that includes connections to concepts and practices in engineering. The title alone suggests the primacy of science in the standards, as is obviously appropriate. *A Framework for K–12 Science Education* (NRC 2012, p. 12), upon which NGSS is based, provides further clarification of the role of engineering vis-à-vis science:

> [E]ngineering and technology provide a context in which students can test their own developing scientific knowledge and apply it to practical problems; doing so enhances their understanding of science—and, for many, their interest in science—as they recognize the interplay among science, engineering, and technology. We are convinced that engagement in the practices of engineering design is as much a part of learning science as engagement in the practices of science.

[9] Taxonomy of Fields and Their Subfields, revised 7/31/06. A resource of the Research Doctorate Programs of the NASEM Board on Higher Education and Workforce, available at https://sites.nationalacademies.org/PGA/Resdoc/PGA_044522.

Like STL, NGSS presents progressions[10] in student learning goals for K–12 engineering (table 2-5). NGSS terms its learning goals "performance expectations," and each combines at least one science and engineering practice, one disciplinary core idea, and one crosscutting concept from the 2012 NRC *Framework*.[11] In addition to serving as standalone standards, the performance expectations for engineering design are integrated with a number of NGSS's disciplinary core ideas in science.

TABLE 2-5 Grade-Band Performance Expectations in NGSS for Engineering Design

K–2 Grade Band	3–5 Grade Band	Middle School Grade Band	High School Grade Band
Ask questions, make observations, and gather information about a situation people want to change to define a simple problem that can be solved through the development of a new or improved object or tool.	Define a simple design problem reflecting a need or a want that includes specified criteria for success and constraints on materials, time, or cost	Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions	Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants
Develop a simple sketch, drawing, or physical model to illustrate how the shape of an object helps it function as needed to solve a given problem.	Generate and compare multiple possible solutions to a problem based on how well each is likely to meet the criteria and constraints of the problem	Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem	Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering
Analyze data from tests of two objects designed	Plan and carry out fair tests in which variables	Analyze data from tests to determine	Evaluate a solution to a complex real-world

[10] Technically, according to NRC (2014, p. 37), "The progressions in the NGSS are not learning progressions as defined in science education research because they neither articulate the instructional support that would be needed to help students achieve them nor provide a detailed description of students' developing understanding. (They also do not identify specific assessment targets, as assessment-linked learning progressions do.) However, they are based on the perspective that instruction and assessments must be designed to support and monitor students as they develop increasing sophistication in their ability to use practices, apply crosscutting concepts, and understand core ideas as they progress across the grade levels."

[11] *Practices* are "the major practices that scientists employ as they investigate and build models and theories about the world and . . . a key set of engineering practices that engineers use as they design and build systems." *Crosscutting concepts* "have application across all domains of science." A *disciplinary core idea* must meet "at least two" of the following four criteria: (1) Have broad importance across multiple sciences or engineering disciplines or be a key organizing principle of a single discipline; (2) Provide a key tool for understanding or investigating more complex ideas and solving problems; (3) Relate to the interests and life experiences of students or be connected to societal or personal concerns that require scientific or technological knowledge; or (4) Be teachable and learnable over multiple grades at increasing levels of depth and sophistication. That is, the idea can be made accessible to younger students but is broad enough to sustain continued investigation over years. (NRC 2012, pp. 30-31)

to solve the same problem to compare the strengths and weaknesses of how each performs.	are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.	similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.	problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts.
		Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.	Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

SOURCE: NGSS Lead States (2013), pp. 183, 207, 244, 291.

In addition to engineering design, both *NGSS*[12] and *STL*[13] propose learning goals related to how engineering affects and is affected by society, influences the environment, connects to disciplines other than those in STEM, and embodies ethical decision making. These topics are critical components of engineering literacy, which is discussed in chapter 3.

CONCLUSION

For many prospective K–12 teachers of engineering, the core ideas and practices of the discipline will be unfamiliar. Many educators, whose own experiences, education, and professional learning have emphasized the notion of getting a single "right" answer, initially may be uncomfortable with the open-ended nature of the engineering design process. For similar reasons, they may be hesitant to accept and treat failure as a normal and expected part of student learning. Beyond these specific potential hurdles, educators may harbor a general fear that engineering is too different or difficult and, as a result, not something they could become skilled at teaching. It is thus encouraging, as the rest of the report will discuss, that K–12 teachers across the country—supported by peers, professional development providers, and others—are introducing students to the concepts, practices, and habits of mind of engineering.

[12] This area is called Science, Technology, Society, and the Environment and is composed of two core ideas: (1) the interdependence of science, engineering, and technology and (2) the influence of engineering, technology, and science on society and the natural world (NRC 2013, pp. 442–446).
[13] These are (1) the cultural, social, economic, and political effects of technology; (2) the effects of technology on the environment; (3) the role of society in the development and use of technology; and (4) the influence of technology on history (ITEA 2007, pp. 57–64).

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3

Goals of K–12 Engineering Education

Numerous and increasing efforts over the past several decades have sought to introduce young people to key ideas in engineering and the practices of engineers. They have ranged from formal, classroom-based curricula aligned with state or national standards to informal, out-of-school initiatives, some with state, national, or even international reach. Some programs focus explicitly on the practices of engineering, using mathematics and science as necessary tools of design; others treat engineering as a context for teaching mathematics and science content; still others use engineering design–based activities primarily as a way to promote student interest and motivation to learn (Milto et al. 2016, p. 265).

The emergence of K–12 engineering programs in diverse contexts with different degrees of emphasis on the practices and disciplines of engineering underscores the need to address a very basic question: What is the goal of introducing engineering into K–12 education? Not surprisingly, there are multiple goals.

By examining extant curricula and programs and related research, the committee identified four goals for K–12 engineering education:

1. Developing engineering literacy.
2. Improving mathematics and science achievement through the integration of concepts and practices across the STEM fields.
3. Improving college and career readiness.
4. For a small percentage of students, preparing for matriculation in postsecondary engineering programs.

We consider each in turn, and then briefly discuss their implications for the preparation of K–12 teachers of engineering (this is addressed more fully in chapter 5).

THE GOAL OF DEVELOPING ENGINEERING LITERACY

The American educational system has a long history of promoting literacy. Perhaps the most foundational literacy concerns the ability to read and write. But even this measure of literacy has varied over time, from being able to write one's name, to having completed the fourth grade (Clifford 1984), to being highly educated (Graff 1986). Although the definitions have varied, being literate has consistently referred to mastering knowledge and processes needed to interpret culturally significant information (de Castell et al. 1986). Desired levels of literacy have expanded beyond reading and writing to include reasoning and other higher-order cognitive skills (Clifford 1984). In addition, the number of those expected to be literate has grown to include virtually everyone, and it is generally recognized that formal schooling is not the sole means of acquiring literacy (Resnick 1990).

More recently, the idea of literacy has been applied to a person's understanding of more specific areas of knowledge, such as science and mathematics. In the STEM fields, the earliest US efforts to define literacy focused on science. In *Science for All Americans* the American

Association for the Advancement of Science proposed that scientific literacy should encompass "the knowledge, skills, and attitudes all students should acquire from their total school experience" (Rutherford and Ahlgren 1991, p. 220). The report describes the scientifically literate person as one who "is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations; understands key concepts and principles of science; is familiar with the natural world and recognizes both its diversity and unity; and uses scientific knowledge and scientific ways of thinking for individual and social purposes" (p. xvii). A recent report from the National Academies of Sciences, Engineering, and Medicine (NASEM 2016), drawing on work from the health literacy community, argues that science literacy is relevant not only to individuals but also to communities and society as a whole. In the latter two contexts, the report notes, literacy can "transcend the aggregation of individuals' knowledge and accomplishments" (p. 4).

Engineering literacy involves understanding concepts such as constraints, specifications, optimization, and trade-offs, and being able to apply the engineering design process. It also involves recognizing the influence of engineering on society and how engineering is different from science in its application to personal, social, and cultural situations. In this way, engineering literacy can help address misconceptions people have about the field. Research has documented, for example, that many K–12 teachers and students have a limited understanding of what engineers do (e.g., Cunningham and Knight 2004; Cunningham et al. 2005, 2006). The goal of engineering literacy also represents an orientation and curriculum emphasis that values learning outcomes for *all* students.

Through the design and improvement of technology, engineers are largely responsible for the human-built world. Engineering and technology are thus intimately connected, so engineering literacy must address issues related to technology. Technologically literate citizens understand basic engineering concepts and terms as well as the nature and limitations of the engineering design process (box 3-1; NAE and NRC 2002).

BOX 3-1
Characteristics of a Technologically Literate Citizen

Knowledge

- Recognizes the pervasiveness of technology in everyday life.
- Understands basic engineering concepts and terms, such as systems, constraints, and trade-offs.
- Is familiar with the nature and limitations of the engineering design process.
- Knows some of the ways technology shapes human history and people shape technology.
- Knows that all technologies entail risk, some that can anticipated and some that cannot.
- Appreciates that the development and use of technology involve trade-offs and a balance of costs and benefits.
- Understands that technology reflects the values and culture of society.

Ways of Thinking and Acting

- Asks pertinent questions, of self and others, regarding the benefits and risks of technologies.
- Seeks information about new technologies.

- Participates, when appropriate, in decisions about the development and use of technology.

Capabilities

- Has a range of hands-on skills, such as using a computer for word processing and surfing the Internet and operating a variety of home and office appliances.
- Can identify and fix simple mechanical or technological problems at home or work.
- Can apply basic mathematical concepts related to probability, scale, and estimation to make informed judgments about technological risks and benefits.

SOURCE: NAE and NRC (2002), p. 17.

Additional insight into the nature of engineering literacy is provided by the three "general principles" for K–12 engineering education identified in *Engineering in K–12 Education: Understanding the Status and Improving the Prospects* (NAE and NRC 2009, pp. 4–5):

1. K–12 engineering education should emphasize engineering design.
2. K–12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills.
3. K–12 engineering education should promote engineering habits of mind, including systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations.

A slightly more expansive model of engineering literacy is presented in *Standards for Professional Development for K–12 Teachers of Engineering* (Farmer et al. 2014). Designed to guide the professional learning of K–12 educators, it broadens the concept to include literacy related to engineering careers. Specifically, the standards suggests that educators (and, by extension, their students) should understand that "Engineering includes multiple areas of specialization (e.g., mechanical, electrical, petroleum, civil, biomedical, aerospace, environmental, industrial); and engineering career pathways are accessible via a variety of educational routes" (Farmer et al. 2014, p. 1). This document will be discussed further in chapter 5.

The idea that K–12 engineering education can serve a general literacy goal is supported by the National Assessment of Educational Progress assessment of Technology and Engineering Literacy (TEL). This first-ever national assessment to target engineering concepts and skills has been administered twice, in 2014 and 2018, to large numbers of US eighth graders across three domains: technology and society, design and systems, and information and communication technology. The framework document used to design the assessment defined technology and engineering literacy as "the capacity to use, understand, and evaluate technology as well as to understand technological principles and strategies needed to develop solutions and achieve goals" (NAGB 2013, p. xi). In addition to asking traditional, multiple-choice questions, the TEL assessment includes a number of scenario-based tasks. One sample task in the 2014 assessment asked students to create a route for a safe bike lane in a city; in another, they had to troubleshoot and fix the habitat for a classroom iguana (Nation's Report Card 2014).

THE GOAL OF IMPROVING MATHEMATICS AND SCIENCE ACHIEVEMENT THROUGH INTEGRATED STEM LEARNING

Another goal for K–12 engineering education is to encourage and support learning in the other three STEM subjects. Engineering is seen as a vehicle for integrated STEM learning in part because design tasks can be highly engaging for students. Indeed, engagement is one of the most consistent and often-reported outcomes of doing engineering with students (Milto et al. 2016), including students not typically engaged in STEM subjects (Purzer et al. 2015). Design challenges also can provide real-world settings where engineering can clearly be seen as doing a "public good" (Hacker et al. 2017). The kinds of real-world problems that students are asked to solve invite both learning and applying concepts from multiple STEM disciplines.

Many approaches to integrated STEM education use the engineering design process as a context for exploring concepts and practices in science (e.g., Kolodner 2002;Kanter 2010) and mathematics (e.g., Huang et al. 2008). For example, student-designed rollercoasters can be used to demonstrate the science concept of potential energy, and mathematics can be used to calculate the average velocity of a ball on the coaster track. K–12 engineering activities, whether in the classroom or at museums or other out-of-school venues, can engage learners in doing scientific investigations (e.g., NASEM 2019) and in using mathematics to predict, model, and analyze the performance of prototypes. Connecting engineering design to concepts in science and mathematics can help students better grasp and frame the challenge, gain insights from studying previous solutions to similar problems, choose among competing possible solutions to the problem, understand the needs of different users, and build better mental models of how prototypes are working and how they should work.

Although empirical evidence for engineering leading to learning or achievement in science and mathematics is mixed (NAE and NRC 2014, pp. 56–60) and the number of high-quality studies in this area is fairly limited, some promising results suggest that students can improve their understanding of science ideas through engineering design. When the learning goal is to apply ("transfer") known science ideas to a design challenge, there is opportunity for students to develop more robust and flexible understandings of those concepts (Spiro et al. 2003). Learning and using mathematics concepts in the context of engineering design may be more challenging for students (e.g., Tran and Nathan 2010).

Beyond improving engagement and learning in science and mathematics, engineering education can enable STEM integration by helping students engage with engineering practices in informed ways rather than through trial-and-error or random guesswork. Informed engineering design involves instructional approaches where (1) learning is "central and inherent to designing" (Adams and Atman 2000, p. 3), whether the learning takes place while sketching, making a prototype, experimenting, or troubleshooting; (2) decisions are driven both by practical knowledge (McCormick 1994; Sternberg 1985) and knowledge of relevant science concepts (Crismond and Adams 2012); (3) design strategies are used effectively (Crismond and Adams 2012); and (4) ideas and practices from different STEM disciplines are used and reflected upon together (Kimbell et al. 1991, p. 156) via explicit connection making (NAE and NRC 2014, pp. 89-90) and the development of STEM associational fluency.[1].

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[1] STEM associational fluency is an "integrated approach to STEM education (iSTEM) [that] includes instructional approaches and complex classroom interventions that interweave content and learning experiences among and between any of the STEM subjects or other school subjects" (de Miranda et al. 2016, p. 4).

While STEM integration is a stated goal of many educators, the cognitive and learning sciences point to certain challenges that may inhibit students' ability to learn in integrated STEM contexts (NAE and NRC 2014, pp. 78–89). We discuss three challenges relevant to engineering-based STEM integration and possible ways to address them.

Cognitive Limits of Attention and Memory

The cognitive load for beginning designers is much greater than for experienced designers. A study of expert designers found that most of their time was spent making routine design decisions, for which solutions from prior work were readily available and recalled from memory (Akin and Lin 1996). In contrast, "novel decisions," where prior knowledge did not avail the designers of useful insight to the design problem, carried a "very large overhead" of time and attention for the experts to resolve. For beginning designers, almost all their design decisions are novel to them. Lack of familiarity with relevant disciplinary domains (e.g., science and mathematics), of knowledge of how devices or systems work, and of the skills needed to make and refine a prototype can overload the learner's short-term memory. This leaves fewer mental resources for making connections to newly acquired abstractions—from two, three, even four distinct disciplines—as the learner moves among the details of the developing prototypes. Design challenges can also be difficult if the knowledge they draw on is "extensive and unpredictable" (McCormick 1993, p. 309) and require meeting multiple needs and requirements that may conflict with one another (Alexander 1964).

Educators can help by giving design challenges that vary in terms of how well they are defined (well defined, moderately ill defined, ill defined) (Jonassen 2000). A well-defined design problem might have only one or two variables that can be changed and could result in a single "best" answer. Materials-constrained design problems can also be well defined, as when students use materials given to them and the problem framing has been done for them. Well-defined and moderately ill-defined tasks can help build domain knowledge or skills in design thinking, when they are appropriately scaffolded (e.g., Crismond 2011), as with Burghardt and Hacker's (2004) "knowledge skill builders" and the "resource tasks" in the Nuffield Design & Technology curricula (Barlex 1995). With such scaffolding, students grapple with some but not all aspects of extremely complex ("wicked") design problems (Churchman 1967; Buchanan 1995). Selected ill-defined design challenges can be used as performance tasks, where students frame the problem to solve (Adams et al. 2003).

Learning from Real-World Situations

Design challenges typically have real-world connections and require making prototypes and physical models, activities with different types of challenges for different types of students. Students with extensive craft knowledge (e.g., mechanical/tool skills, experience making and constructing) and no training in science, for example, can often offer very workable solutions to such challenges that short circuit the need to use and apply STEM concepts. Providing these students with just-in-time learning of relevant science and mathematics concepts (e.g., Burghardt and Hacker's [2004] "knowledge and skill builders") can help address this situation. For students with limited craft knowledge, the "perceptual richness" (Goldstone and Sakamoto 2003) of real-world design tasks can draw attention away from acquisition of STEM ideas and practices. The challenge of *making* can be all-absorbing for these students and demand significant cognitive and attentional resources.

Making Connections among Multiple Representations

As indicated in the preceding two sections, integrated STEM learning involves making connections between concepts and their representations (NAE and NRC 2014, pp. 81–82), but in some cases representations of the same concept can mean different things in different STEM fields. For example, modeling is one of the most powerful activities and notions in all STEM subjects. In technology, it may involve building a physical artifact to scale. In science, models, which are simplifications of more complex phenomena, may be created in order to make predictions and refine explanations about facets of the natural world. Engineers may use mathematical models to predict the performance of key features of a design, such as how quickly a disk brake cools depending on its thickness and diameter, or how varying the length of the throw arm of a catapult affects how far its projectile travels.

Teachers can help students who struggle to reconcile different representations of similar phenomena by highlighting the STEM field the current discussion addresses and asking how models in this field and context are similar and different with examples of models from other fields and contexts. Cognitive flexibility theory (Spiro et al. 1995) suggests that using multiple examples of concepts in different contexts can lead to more flexible understanding and use of those ideas, especially in ill-structured contexts (Spiro et al. 1995), such as those posed by engineering design challenges. Techniques, such as connecting past instructional moves to those in the past or future, have been found to support "cohesion" of important science and mathematics concepts in K–12 engineering education (Nathan et al. 2017).

As this brief review suggests, there may be challenges to learning STEM concepts and practices in an integrated way. However, repeated experience with ideas that cross STEM boundaries in the context of engineering design activities can reduce challenges related to cognitive limits, real-world problem solving, and multiple representations.

THE GOAL OF IMPROVING PREPARATION FOR COLLEGE AND CAREER

Data from a variety of sources suggest broad consensus on the types of skills and dispositions young people entering college or the workforce should have. For example, large majorities of respondents to a 2018 employer survey by the National Association of Colleges and Employers (NACE 2018) said they looked for evidence of written communication skills (selected by 82 percent of employers), problem-solving skills (selected by 81 percent), and ability to work in a team (selected by 79 percent) on a job candidate's resume. The American Association of Colleges and Universities has commissioned multiple surveys of employers about the level and breadth of desired knowledge and skills they seek when hiring. The resulting data (e.g., Hart Research Associates 2015) suggest that for long-term career success, a job applicant's demonstrated capacities for critical thinking, clear communication, and complex problem-solving are more important than any specific undergraduate major. Of 17 outcome areas tested, employers valued most highly teamwork skills, written and oral communication, critical thinking, ethical decision-making, and the ability to apply knowledge in real-world settings.

The Council of Chief State School Officers (CCSSO 2013), which represents public sector K–12 education administrators, has proposed a definition of college, career, and citizenship readiness that builds on these employer-identified traits (box 3-2). The definition overlaps significantly with visions of college and career readiness described by a number of states (Mishkind 2014).

BOX 3-2 College, Career, and Citizenship Readiness

"College, Career, and Citizenship Readiness" means that students exit high school qualified to enroll in high-quality postsecondary opportunities in college and career, including the U.S. Military, without need for remediation and equipped with the knowledge, skills and dispositions to make that transition successfully. This means that all students must graduate having mastered rigorous content knowledge and demonstrated their ability to apply that knowledge through higher-order skills including but not limited to critical thinking and complex problem solving, working collaboratively, communicating effectively, and learning how to learn. Students must also be prepared to navigate the pathways and systems that will allow them to gain access to positive postsecondary opportunities.

SOURCE: CCSSO (2013), p. 6.

The college and career readiness skills sought by postsecondary educators and employers are variously called 21st century skills, professional skills, new basic skills, and higher-order thinking. These terms typically refer to both cognitive and noncognitive skills—critical thinking, problem solving, collaboration, effective communication, motivation, persistence, and learning to learn—that can be demonstrated in core academic content areas and are important to success in education, work, and other areas of adult responsibility. The labels also may include other important capacities—such as creativity, innovation, and ethics—that are important to later success and may also be developed in formal or informal learning environments (NRC 2012b, p. 17). College and career readiness competencies are particularly important to the extent that they encourage deeper learning, the ability to transfer understanding and capability between contexts within a single domain or from a context in one domain to another.

College and career readiness does not mean that K–12 students who experience engineering coursework are necessarily aiming for careers or further study in engineering, although this may be true for some (see next section, Preparation for Matriculation in Engineering Programs). But whether or not one majors in engineering, elements of engineering education align with the worker characteristics sought by many employers and with student traits desired by higher-education institutions. These include engineering's orientation toward systematic identification and problem solving, integration of concepts and practices across multiple subject areas, communication skills, attention to ethical concerns, and teamwork.

There is limited empirical evidence that engineering coursework in grades K–12 can contribute to college readiness. A study of the Project Lead The Way (PLTW) program[2] found higher levels of both mathematics proficiency and enrollment in institutions of higher education among PLTW students compared with a matched comparison group (Van Overschelde 2013). Other research on PLTW failed to document increased enrollments but did find that a larger proportion of PLTW students than non-PLTW students chose to major in a STEM subject (Pike and Robbins 2014).

[2] Project Lead The Way is a nonprofit organization that develops STEM curricula, including in engineering, for use by US elementary, middle, and high schools and provides teacher professional development.

THE GOAL OF PREPARING FOR MATRICULATION IN ENGINEERING PROGRAMS

A final goal of K–12 engineering education is to help prepare students who may wish to matriculate in postsecondary engineering programs. This preparation may involve the nurturing of interest in engineering, including as a possible career path; development of an engineering identity; and pursuit of science and mathematics coursework that provides a foundation for college-level engineering studies.

Nurturing Interest in Engineering

Students' interest positively affects their attention, goals, and levels of learning (e.g., Hidi and Renninger 2006; Renninger and Hidi 2011). Interest is also related to identity: once interest has been triggered and develops, the student begins to identify "with the goals, actions and topics related to these interests" (Krapp 2007, p. 14; Renninger 2009).

Interest (and identity) development in K–12 education has been studied more extensively in science than in the other STEM disciplines; there is little research on interest development in engineering specifically. Nonetheless, studies show that various K–12 programs and activities in engineering enhance students' interest.

As noted, many K–12 integrated STEM initiatives have an engineering design component. They may also share features with learning experiences known to support interest development. Ideally, such learning experiences (1) are open-ended enough to provide learners with a range of "triggers," which may catch attention through promoting novelty, complexity, incongruity, uncertainty, or surprise and (2) include interactions with others, such as educators, parents, and peers, who can model STEM problem solving (Renninger 2012).

A review of outcomes data from 11 afterschool STEM programs found that participation increased students' interest in, capacity to engage productively with, and valuing of STEM (Krishnamurthi et al. 2014). And in one of the programs, TechBridge, 85 percent of girls reported finding engineering more interesting after participation. Similarly, a large survey of college students who participated in one or more engineering or robotics competitions during high school found a 5 percent greater interest in STEM careers by the end of high school compared with students who did not engage in such competitions (Miller et al. 2017). The study also found that participation in a robotics or engineering competition predicted interest in a career in engineering (but not in any other STEM subdiscipline). For example, participation in FIRST (www.firstinspires.org) robotics competitions influences not only student course selection in college but also choice of career. An ongoing longitudinal study of the program finds these students show greater interest in STEM careers, gains in STEM identity, and improvements in STEM understanding (Melchior et al. 2018).

The committee found one study examining the potential impact of classroom engineering activities on choice of college major. According to Zarske et al. 2007, students in grades 3–12 who experience once-weekly engineering projects may be more likely to apply to engineering schools.

Developing an Engineering Identity

A fair amount is known about engineering identity development in college students and working professionals (e.g., Morelock 2017; NAE 2018, pp. 94–97; Tonso 2014). Few researchers have examined the development of engineering identity in K–12 students, but the foundation for STEM-related identity development at the K–12 level involves (1) getting young people interested in STEM topics and professions, (2) developing their competence and confidence, and (3) helping them envision themselves as contributors and participants in the STEM enterprise (Krishnamurthi et al. 2014, p. 8).

The Engineering Identity Development Scale (EIDS) is designed to measure engineering identity development in preadolescents (Capobianco et al. 2012). It was tested among several hundred elementary students taking introductory engineering lessons, including a unit of the *Engineering Is Elementary* curriculum, and showed that the interest levels of both girls and boys increased as a result of their learning experience (Douglas et al. 2014). Another study that also used the EIDS determined that lessons that integrated science, technology, and engineering were more likely to boost engineering identity among elementary students, compared to a matched control group (Yoon et al. 2014).

Pursuit of Science and Mathematics Coursework

Generally speaking, young people who aspire to be engineers need to pursue advanced-level courses in science and mathematics in high school to satisfy entry requirements for college engineering programs. Overall, the more high school science and mathematics courses a student takes in high school, the more likely they are to earn a STEM degree (Eagan et al. 2010). Although many individual and institutional factors affect whether a student completes an undergraduate engineering degree (Hughes et al. 2013; NAE 2018), some research has suggested that a student who takes several years of high school mathematics slightly increases their odds of earning an engineering degree within 5 years of matriculation (Hughes et al. 2013). Taking advanced high school mathematics and science courses predict grades in college calculus courses (Tyson 2011), which may affect whether a student continues in an engineering course of study. Students who did not complete calculus in high school were more likely to transfer out of engineering and into another STEM degree program than those who did (Tyson 2011).

Some of this preparation can come through dual-credit programs, dual-enrollment programs, Advanced Placement (AP) courses, or any other arrangement in which high school students take college-level courses. A new model involves a collaboration between the College Board, which oversees the AP program, and PLTW. AP + PLTW offers students recognition for completing a combination of AP and PLTW courses in engineering, biomedical science, or computer science. In the 2016–17 school year, over 2,300 students received recognition in engineering (Howell 2018), which PLTW says “demonstrates to colleges and employers that the student is ready for advanced course work and interested in careers in this discipline.”[3] In addition, as noted in chapter 1, a consortium of universities are pilot testing an advanced high school course in engineering that may form the basis of an AP offering. However, unequal access to AP coursework, particularly for students at high-need schools (Handwerk et al. 2008) that also tend to have less experienced teachers and fewer science facilities (Smith et al. 2013), may compound the lack of diversity in engineering.

EMPHASIS AND OVERLAP OF THE FOUR GOALS

[3] AP + PLTW: Preparing Students for College and Careers. Available online at https://www.pltw.org/our-programs/ap-pltw (accessed August 7, 2018).

So far, this chapter has considered the four goals for K–12 engineering education separately. In classrooms and other learning environments, however, multiple goals may be relevant.
For example, the goal of literacy would seem a priority for younger students. And the structure of the elementary grades, where teachers are responsible for more than one subject, offers opportunities to help students begin to connect engineering to basic ideas and practices in science and mathematics as they tackle simple design challenges. Grades K–5 are also not too early for students to begin to develop qualities valued in college and career settings, which align with many of the essential qualities of engineering described in chapter 2. For example, acceptance of failure as a necessary part of the engineering design process can be nurtured beginning in elementary school (Lottero-Perdue 2015; Lottero-Perdue and Parry 2017).

In the middle and upper grades, where teachers are more likely to be subject-matter specialists, STEM integration may become more important, with students leveraging more and increasingly complex concepts from science and mathematics to address engineering design challenges. The goal of preparing for matriculation in college engineering programs, with their high-level science and mathematics coursework, will be relevant to some high school students, but all high school students will benefit from mastery of the skills and attributes valued by employers and postsecondary institutions. None of the goals suggests engineering is out of reach as a potential career path for any student.

The relative emphasis of the four goals and their overlap will vary depending on local and state educational goals as represented by standards and other policy documents, the curriculum or school, the number and expertise of engineering teachers, and other factors. Figure 3-1 shows how the goals might play out across K–12 in a particular setting.

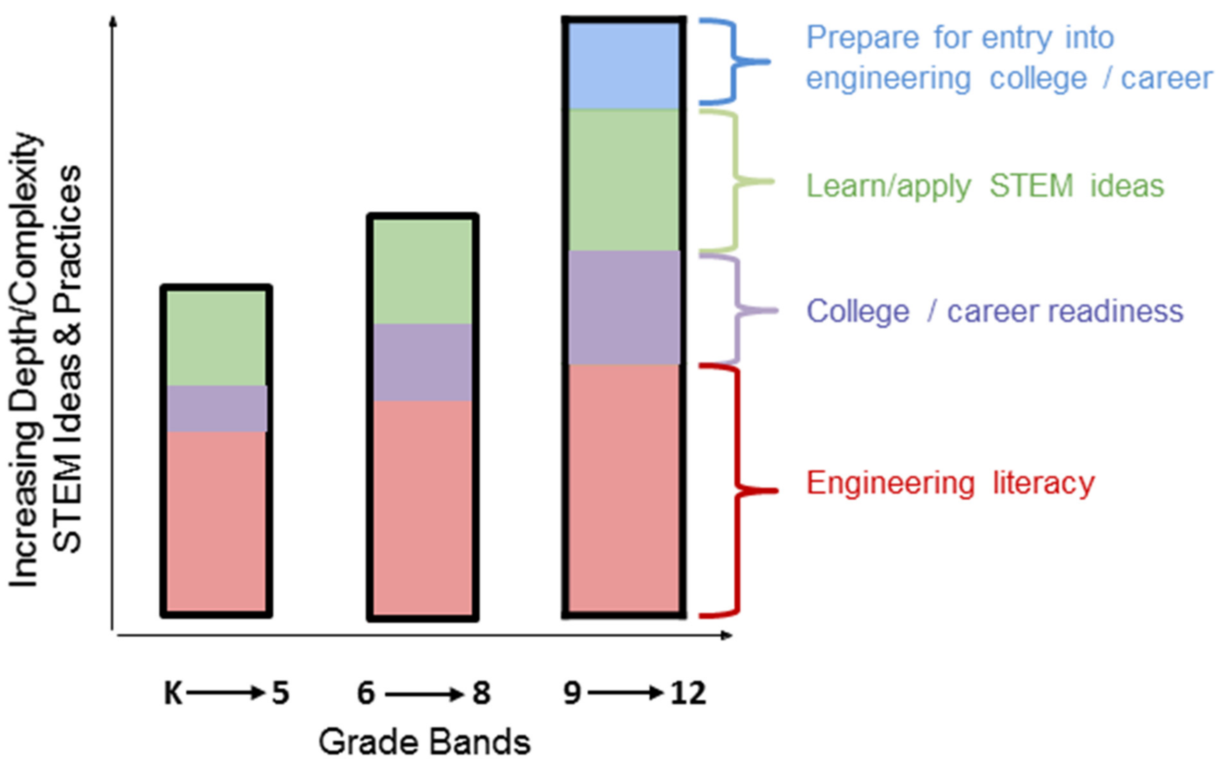

FIGURE 3-1 Notional Representation of the Four Goals of K–12 Engineering Education in Relation to Grade Bands and Depth/Complexity of STEM Ideas and Practices (created by the committee)

CONCLUSION

Engineering plays a central role in the design of technologies, systems, and services that address human needs and wants. Engineering know-how is also required to address the inevitable unintended, sometimes negative, consequences associated with some of these innovations. It is thus fitting that the first goal of K–12 engineering education is engineering literacy. A person who is engineering literate has a basic understanding of the people and processes involved in creating the human-built world. With this foundation, she can think critically and make decisions about a variety of important issues important to her, her family, and her community. Similarly, the second and third goals of K–12 engineering education empower students in different ways to be competent, engaged members of society, whether or not they pursue an engineering degree. The fourth goal is important to students interested in an engineering career.

Accomplishing these laudable goals requires a knowledgeable and confident teacher corps. As we show in chapter 4, some of these educators are already in the classroom, though there are uncertainties about their numbers and the extent of their engineering literacy.

As noted in chapter 2 (“Engineering and Diversity”), engineering has had historical difficulty attracting women and underrepresented minorities to the field. Chapter 4 (“Demographics and Diversity”) notes the paucity of these populations in the current workforce of K–12 teachers of engineering. This suggests that all of the goals for K–12 engineering education will be more impactful if informed by diversity considerations. A more diverse student population, given equitable access to engineering learning opportunities, will be the seed stock for future K–12 teachers, including teachers of engineering.

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4

The Workforce of K–12 Teachers of Engineering

To draw conclusions and make recommendations about the country's current and future needs for engineering-literate K–12 teachers, it would be useful to know something of the make-up of the current workforce of these educators, such as their numbers, demographic characteristics, and levels of preparation. Information is also needed about the educational programs involved in preparing new K–12 teachers of engineering (e.g., schools of education) and in providing engineering-focused professional development opportunities to those already working in the classroom. Beyond the numbers, it would be helpful to understand the educational pathways and related policies, such as credentialing, that support or hinder an individual from becoming a K–12 teacher of engineering. This chapter addresses all of these important issues. As a reminder and as will be clear in what follows, the committee is using the term "teacher of engineering" to refer to any elementary or subject-matter secondary teacher who spends some portion of the school day providing engineering instruction.

CHARACTERISTICS OF THE WORKFORCE

In an effort to shed light on how many K–12 educators are currently teaching engineering, the committee examined data from the federal National Teacher and Principal Survey (NTPS),[1] administered by the US Department of Education's National Center for Education Statistics (NCES). These survey data provide estimates of the number of public-school educators working in various subject areas along with relevant demographic information, such as educational background and certification status.[2]

Size of the Workforce

The most recent NTPS teacher questionnaire (2015–16) was filled out by a sample of 31,950 K–12 teachers and weighted to be nationally representative.[3] One question asked respondents to pick from a long list the subjects, up to a maximum of 10, they taught during the school year. The subjects were assigned numerical codes and organized into categories. For the committee's analysis, three subjects are of interest: engineering (code 214, part of the natural sciences[4] category); construction trades, engineering, or science technologies (including CADD [computer-aided design and drafting] and drafting, code 246, part of the career or technical

[1] The NTPS is a redesigned version of NCES's School and Staffing Survey (SASS).
[2] Additional information is available at https://nces.ed.gov/surveys/ntps/ (accessed August 10, 2018).
[3] The weighted total number of K–12 teachers, according to NCES, was 3,827,170. The agency recently announced it was reevaluating the weights developed for the teacher data due to concerns the numbers may have been improperly inflated. NCES says it will rerelease the new data in 2020.
[4] The natural sciences are concerned with the description, prediction, and understanding of natural phenomena. The two main branches of the natural science are the biological, or life, sciences, and the physical sciences (physics, chemistry, astronomy, and Earth science).

education category); and industrial arts or technology education (code 255, also part of career or technical education).[5] These data are presented in table 4-1, which, for comparison, includes the number of teachers who said they taught science, mathematics, and English and language arts.

TABLE 4-1 Engineering, Science, Mathematics, and English and Language Arts Teaching Assignments, 2015–16

Subject (code)	Unweighted Sample Size	Weighted Sample Size
Industrial arts or technology education (255)	380	40,960
Construction trades, engineering, or science technologies (including CADD [computer-aided design and drafting] and drafting) (246)	180	19,280
Engineering (214)	90	8,710
All natural sciences	3,200	345,940
Mathematics (excluding computer science)	3,680	397,310
English and language arts	5,200	599,600

SOURCE: Calculations based on data from the 2015–16 National Teacher and Principal Survey. All samples are rounded to the nearest 10 to conform to reporting requirements of the National Center for Education Statistics.

In the prior NCES teacher survey, the 2011–12 School and Staffing Survey, no respondents indicated that they taught engineering as a natural science field; they exclusively reported teaching one of the two career and technical education (CTE)–related versions of engineering. The lack of any non-CTE engineering teachers in the previous survey is not due to a coding decision by NCES staff, because respondents select their teaching assignments. The previous survey was fielded prior to publication of the Next Generation Science Standards (NGSS), which prominently and explicitly connect engineering concepts and practices to the natural sciences. Even before NGSS, however, a handful of states included engineering content in their K–12 curriculum frameworks for science education (Carr et al. 2012). One possible explanation for the absence of self-identified "engineering" teachers in the prior survey could be that the number of such educators was simply too small to be captured in the survey sampling frame. For the purposes of this project, data on the two CTE-related teacher categories do not provide the degree of specificity the committee would like. In the case of code 246, because the subject includes not only engineering but also construction trades, science technologies, drafting, and CADD, it is not possible to know how many respondents selected this option to indicate that they teach engineering as opposed to one of the other subjects. In the case of code 255, because of the history of technology education (box 4-1), the committee does not have great confidence that all NTPS respondents who selected this teaching assignment were, in fact, teachers of engineering.

[5] We include industrial arts or technology education because over the past 18 years the field of technology education has focused increasingly on the teaching of engineering. (For details of this history, see NAE and NRC 2009, pp. 31–33, and NAE and NRC 2014, pp. 17–18.) See also the discussion of the Standards for Technological Literacy in chapter 2, Science and Mathematics in the Service of Engineering.

BOX 4-1
Technology Education

Technology education, which until the mid-1980s was called industrial arts, has been in flux for decades. Publication of the *Standards for Technological Literacy* (ITEEA 2007) included a major new emphasis on engineering and engineering design in K–12 technology education. Reflecting this shift, in 2010 the group representing these teachers, the International Technology Education Association, changed its name to acknowledge the increasing emphasis on engineering in curriculum and the preservice preparation of its educators: it is now called the International Technology and Engineering Educators Association, (ITEEA). The field's embrace of engineering has not been universal, however, and the technical instruction in current teacher preparation programs varies in its inclusion of courses in engineering and in higher-level mathematics and science useful in engineering design (Litowitz 2014). Thus technology education is still best thought of as a continuum of practices spanning traditional industrial arts ("shop") classes, career-focused industrial technology, and technology education programs that include differing degrees of engineering content.

The varied implementation of technology education makes it difficult to clearly distinguish from K-12 "engineering education." The distinctions are most clear between the industrial arts model of technology education, with its emphasis on tool skills and fabrication of technological artifacts, and engineering education that focuses on the engineering design process as an approach to problem solving.

SOURCE: Adapted from NAE and NRC 2009, pp. 31-33.

For the remainder of this section, we combine data for natural science engineering teachers and teachers of "construction trades, engineering, or science technologies" and refer to this combined dataset as "engineering teachers." Otherwise, in many cases the sample size of natural sciences engineering teachers would be too small to analyze separately.

In addition to reporting up to 10 teaching areas, NTPS respondents are asked to identify their "main" teaching area. About 10 percent of engineering teachers, representing .07 percent of the weighted sample of all K-12 teachers, indicated that this was engineering, but the largest share identified construction trades, engineering, or science technology as their main area (table 4-2). Ten percent of engineering teachers identified one of several science subjects as their main area of teaching.

TABLE 4-2 Main Teaching Area of Engineering Teachers, in Areas Accounting for 2 Percent or More of Teachers, Weighted Values

Teaching Area	Number	Percent
Construction trades, engineering, or science technology	14,790	52.80
Industrial arts or technology education	3,130	11.20
Engineering	2,660	9.50

Science, general	810	2.90
Physics	780	2.80
Physical sciences	620	2.20
Biology or life sciences	570	2.10

SOURCE: Calculations based on data from the 2015–16 National Teacher and Principal Survey. All samples are rounded to the nearest 10 to conform to reporting requirements of the National Center for Education Statistics.

Among those who taught industrial arts or technology, 64.2 percent said that this was their primary teaching assignment (table 4-3). An additional 4.0 percent of industrial arts teachers identified "construction trade, engineering, or science technology" as their main teaching area. Compared with engineering teachers, science and mathematics were much less prevalent as main teaching areas for industrial arts and technology teachers.[6]

TABLE 4-3 Main Teaching Area of Industrial Arts or Technology Teachers, in Areas Accounting for 2 Percent or More of Teachers

Teaching area	Number	Percent
Industrial arts or technology education	26,280	64.2
Other career or technical education	2,880	7.0
Construction trades, engineering, or science technology	1,650	4.0
Computer science	1,350	3.3
Business management	1,200	2.9
Other	950	2.3
Communications and related technologies	810	2.0

SOURCE: Calculations based on data from the 2015–16 National Teacher and Principal Survey. All samples are rounded to the nearest 10 to conform to reporting requirements of the National Center for Education Statistics.

Another, more indirect, way to estimate the number of teachers working in a field is to determine how many schools offer courses in the subject. For instance, a 2018 national survey of science and mathematics educators found that 46 percent of high schools in the sample[7] offered at least one engineering course[8] (Banilower et al. 2018); 31 percent offered non-college-preparatory and 29 percent offered first-year college preparatory engineering courses; and 17 percent offered a second-year engineering course. Taking the first data point, and assuming that an engineering course is taught by a single teacher, it is possible to estimate the number of such educators if one also knows the number of high schools in the United States. A 2011 estimate based on NCES data reported about 23,000 public and 7,300 private high schools, or about 30,300 in total, in the 2009–10 school year (Mathews 2011). Taking 46 percent of this number

[6] Industrial arts or technology education teachers' main science teaching areas included "science, general" (0.6 percent), chemistry (0.5 percent), physics (0.4 percent), physical sciences (0.3 percent), and "biology or life sciences" (0.2 percent).

[7] The sample included charter and magnet schools, but there were too few of these institutions to break out data for them separately (E. Banilower, Horizon Research, personal communication, November 5,2019).

[8] The survey instructed teachers to consider engineering courses as those that "address the nature of engineering, engineering design processes, technological systems, or technology and society. Do not include career-technical education (CTE) courses that cover such things as automotive repair, audio/video production, etc." (Banilower 2018, p. C-15).

suggests there may have been as many as 14,000 high school educators teaching at least one engineering course in 2018. Presumably, this number would not include technology education teachers, although their field has made a turn toward engineering over the past two decades.[9]

This approach has shortcomings. For one thing, it does not allow estimates for engineering teachers working in middle and elementary schools, because those institutions were not asked about engineering courses in the research by Banilower and colleagues. In fact, there are a number of engineering curricula aimed at middle school students (NAE and NRC 2009, pp. 74–75), and one of the most established K–12 engineering curriculum programs in the country, with teachers delivering the curriculum in every state, is Engineering is Elementary (www.eie.org), designed for elementary students. Furthermore, there is well-documented public confusion about what engineering is (e.g., NAE 2008), and the survey instrument itself may have introduced uncertainty among respondents because of the way it defined engineering.[10] It is thus possible that survey respondents either failed to identify courses that were engineering-focused or identified courses as engineering—such as those in the computer sciences, for example—that were not.

In summary, the available data sources have a number of limitations that hampered the committee's ability to estimate the number of K–12 teachers of engineering. These limitations relate both to the structure of the survey instruments and to the wording of specific survey items. Even considering the noted shortcomings of NTPS for our purposes, it is sobering that less than one-tenth of 1 percent of all K-12 teachers considered themselves to be teaching engineering as their main assignment.

Demographics and Diversity

NTPS also provides demographic information about engineering and technology education or industrial arts teachers. The committee was particularly interested in the race/ethnicity and gender makeup of this population, since the engineering discipline has struggled to attract women and people of color to the field.

Just 20 percent of K–12 engineering teachers are women, the same share as graduate from undergraduate engineering programs but significantly higher than the rate of female graduation from programs in engineering technology. Engineering technology is a close cousin to traditional engineering (see box 6-2) that that provides students with more hands-on, laboratory-based coursework at the two- and four-year college level (NAE 2017, pp. 22–29). The percentage of female technology teachers, at 40 percent, is much closer to parity. The vast majority of teachers in both groups are white, largely mirroring the composition of the US K–12 teacher workforce. These various comparisons are summarized in table 4-4.

TABLE 4-4 Race/Ethnicity and Gender of K–12 Engineering and Technology Education or Industrial Arts Teachers and Degree Earners in Engineering and Engineering Technology Compared with Those in the US Population and K–12 Teacher Workforce, Percent, Various Years

[9] Guidance to teacher participants in the survey says: "For the purposes of this study, the following are not considered computer science, mathematics, science or engineering courses: Health, Hygiene, *Technology Education*, Business, Career-technical education (CTE) courses that cover such things as automotive repair or audio/video production" (emphasis added; Banilower et al. 2018, p. 233).

[10] Guidance regarding engineering to survey respondents said, "This category includes such courses as: Engineering, Engineering Design, Principles of Engineering, Technological Systems, and Technology and Society" (Banilower et al. 2018, p. 234).

	White	African American	Hispanic	Female
K–12 engineering teachers[a]	81.6	4.5	8.9	19.9
K–12 industrial arts or technology teachers[a]	87.8	4.8	5.0	40.3
4-year engineering degree recipients[b]	61.5	3.8	9.6	19.8
4-year engineering technology degree recipients[b]	63.6	10.7	10.0	12.0
US population[c]	76.5	13.4	18.3	50.8
US K–12 public school teacher workforce[d]	80.1	6.7	8.8	76.6

[a] Calculations from the 2015–16 National Teacher and Principal Survey. All samples rounded to the nearest ten to conform to National Center of Education Statistics (NCES) reporting requirements.
[b] Calculations from the 2014 Integrated Postsecondary Education Data System; population of institutions from the NCES.
[c] Estimates for 2018; Source: US Census Bureau (2018).
[d] Estimates for 2015–16 school year; Source: NCES (2017), table 209.10.

Education and Certification

Along with knowledge of students and pedagogy, teacher content knowledge is a critical component of effective teaching. In K–12 STEM education, teachers' degrees and college course taking are often used as proxies for STEM content knowledge. More direct measures of teacher content knowledge as well as confidence to teach may provide a better indication of a teacher's ability to improve student achievement than degree status (see chapter 5, pp. XX-XX). Among the STEM subjects, efforts to develop more effective measures of teacher content knowledge are most developed in mathematics; considerably more research is needed to develop and test such indicators in science and, especially, in engineering (NRC 2013, p. 23).

Lack of documented subject-matter expertise among some K–12 teachers has led to concerns about their capacity to effectively support student learning. For example, one recent study reports that only 3 percent of elementary and 42 percent of middle school science teachers have a degree in science or engineering (Banilower et al. 2018, table 2.6),[11] and it is highly likely that for the vast majority of these educators, the degree is in a science field, not engineering. The prevalence of science teacher's with degrees in science varies according to sub-discipline. In the life sciences, 40 percent and 63 percent of middle and high school teachers, respectively, hold a degree in the field. By comparison, just 5 percent of middle school and 15 percent of high school earth science teachers hold a degree in that subject (table 2.15). The situation is similar in mathematics. While nearly 80 percent of high school mathematics teachers have a degree in either mathematics or mathematics education, only 45 percent and 3 percent of middle school mathematics teachers and elementary teachers, respectively, hold such degrees (table 2.6).

The same study found that only 3, 10, and 13 percent, respectively, of elementary, middle, and high school science teachers had taken at least one college course in engineering. In contrast, the share of science teachers who had taken at least one science course ranged from 31 to 95 percent, depending on grade band and science discipline (Banilower et al. 2018, table 2.7).

Data from NTPS reveal that fewer than half of engineering teachers have engineering-specific certification or education (we discuss certification at greater length in chapter 5). Only

[11] Seventy-nine percent of high school science teachers had at least one of these degrees in 2018, according to Banilower et al. (2018).

19.4 percent of all K–12 engineering teachers majored or minored in engineering, although 41.9 percent are certified to teach engineering (table 4-5). To a certain extent, formal education and certification substitute for each other: many engineering teachers have either an engineering degree or an engineering certification, but not both. Just over a third of engineering teachers who majored or minored in engineering are not certified to teach the subject (1,900 out of 5,430). Almost 70 percent of teachers certified to teach engineering did not major or minor in engineering (8,190 out of 11,720). Fewer than 13 percent of all engineering teachers are both certified to teach engineering and majored or minored in engineering.

TABLE 4-5 Education and Teaching Certification of Engineering Teachers

	Number	Percent
Majored or minored in engineering*	5,430	19.4
Certified to teach engineering♦	11,720	41.9
Majored or minored in engineering,* but NO certification to teach engineering♦	1,900	6.8
Certified to teach engineering, ♦ but NO major or minor in engineering	8,190	29.3
BOTH certified and majored or minored in engineering* ♦	3,530	12.6
NEITHER certified nor major or minored in engineering* ♦	14,360	51.3
Total engineering teachers	27,980	100.0

*In this table, “engineering” majors or minors include both (1) degrees in natural sciences engineering and (2) degrees in construction, engineering, and science technologies. In addition, the survey question that produced these data asked about any major or minor, not the first degree a person earns; a person minoring or majoring in engineering may have other degrees.

♦ The National Teacher and Principal Survey does not include an answer choice for “engineering” in the items that ask about certification. Thus in this table “Certified to teach engineering” means the educator is certified in “construction, engineering, or science technologies.” The committee was not able to determine whether any states have actually certified a K–12 “engineering” teacher, even though some states appear to offer such an option. This topic is discussed later in this chapter.

SOURCE: Calculations from the 2015–16 NTPS. All samples are rounded to the nearest ten to conform to NCES reporting requirements. Reported percents and numbers may diverge slightly due to rounding.

Information about the education and certification of industrial arts or technology education teachers is presented in table 4-6. These teachers have higher rates of majoring or minoring in the subjects they teach (30.8 percent) and of certification in those subjects (47.2 percent) than engineering teachers do in their field. Also unlike engineering teachers, the large majority, about 89 percent, of industrial arts or technology education teachers who majored or minored in one of those fields was certified to teach. Fewer industrial arts or technology education teachers, about 58 percent, were certified to teach one of those subjects and also majored or minored in one of them. Nevertheless, almost half of these educators (49.4 percent) had neither a certification nor a major or minor in industrial arts or technology education.

TABLE 4-6 Education and Teaching Certification of Industrial Arts or Technology Teachers

	Number	Percent
Majored or minored in industrial arts or technology education	12,610	30.8
Certified to teach industrial arts or technology education	19,340	47.2
Majored or minored in industrial arts or technology education, but NO certification to teach industrial arts or technology	1,370	3.3

Certified to teach industrial arts or technology education, but NO major or minor in industrial arts or technology education	8,100	19.8
BOTH certified and majored or minored in industrial arts or technology education	11,240	27.4
NEITHER certified nor major or minored in industrial arts or technology education	20,250	49.4
Total industrial arts or technology education teachers	40,960	100.0

SOURCE: Calculations from the 2015–16 NTPS. All samples are rounded to the nearest ten to conform to National Center of Education Statistics reporting requirements. Reported percents and numbers may diverge slightly due to rounding.

NTPS also asks teachers to indicate their first college major. A plurality (19 percent) of engineering teachers do not have a bachelor's degree at all. Recalling that this category includes those who teach construction, engineering, and science technologies, the high percentage of non-degree-holders may reflect the movement of skilled tradespersons with alternative qualifications, such as 2-year degrees or industrial certifications, into teaching. A small share (13.9 percent) majored in "industrial arts or technology education," 11.3 percent majored in "construction trades, engineering, or science technologies," and only 6.3 percent majored in "engineering." Just as most nonengineering certifications held by engineering teachers were in closely related CTE, science, or mathematics fields, most nonengineering first majors reported by engineering teachers are in CTE, science, or mathematics fields.

The degree history of industrial arts or technology teachers is quite different. The plurality of these teachers (27.4 percent) had a first major in industrial arts or technology education, followed by 14.1 percent in business management and 10.5 percent in elementary education. A small share, 5.8 percent, of industrial arts teachers had no bachelor's degree at all, fewer than was the case for engineering teachers. Although 13.9 percent of engineering teachers had their first major in industrial arts, only 1.8 percent majored in "construction trades, engineering, or science technologies, " and just 0.9 percent of industrial arts or technology teachers had their first major in engineering. The latter point is worth emphasizing, because it stands in contrast to the field's declared turn toward engineering a decade ago.[12] Combined with evidence about the limited extent of engineering coursework in technology teacher preparation programs, noted in the following section, this reinforces the challenges associated with assuring this cohort of teachers of K–12 engineering has relevant content expertise.

Although the exact numbers are unknown, a small number of individuals enter K–12 teaching after working as engineers (box 4-2). These new teachers might complete a bachelor's degree in education or an alternative certification program to develop skills in teaching lesson planning, and classroom management, and to learn to work productively with other teachers (Grier and Johnston 2009). In interviews, many of these teachers state that the skills they acquired in their previous careers were also valuable for teaching (Chambers 2002; Grier and Johnston 2009) and enabled them to engage and motivate students (Muller et al. 2014).

BOX 4-2
Transitioning from Being an Engineer in Industry to a K–12 Teacher

My journey from the corporate office to the classroom was both scary and rewarding. The decision to leave behind my job as a professional engineer to enter the classroom allowed me

[12] In 2010 the International Technology Education Association changed its name to the International Association of Technology and Engineering Educators, reflecting the field's increasing emphasis on engineering education.

to combine my passions as an engineer and an educator to make a difference in my community. I initially did not know where to start. I had no prior formal training in education and there were few resources available to leverage, so I was forced to use my own experiences of learning to guide my initial process. I had to learn how to write curriculum, become comfortable with the pedagogy required to teach engineering, learn how to scaffold learning, and think about what would be fun and engaging for students. Stepping into the classroom was a whole new world and I wanted to make sure that I was fully prepared to take advantage of the opportunity to inspire the students in my afterschool program.

As I began the process of creating a curriculum for my class I first thought about the goals that I wanted students to accomplish and what strengths I had as an engineer to contribute. I began to research various teaching models and consulted friends who were teachers about how best to engage youth. I ended up adopting many of the principles associated with PBL (project-based learning), supporting my students as they gained knowledge and skills by investigating and responding to an engaging, authentic, and complex question, problem, or challenge. I also narrowed down my subject matter to focus on mechanical and electrical engineering principles, since that is where I felt most comfortable. I think it is very important for engineers to work within their own strengths when getting started in education. This allowed me to teach students about subjects that I was very passionate about and felt comfortable creating content around.

I recognized early on that the class would be a marathon and not a sprint and wanted to scaffold students' learning over the course of the year. I began engaging students in simple engineering challenges to get them comfortable utilizing the engineering design process to solve problems and then began elevating the curriculum to have students solve more long-term group projects that incorporated various mechanical and/or electrical engineering principles. I also allowed room for the students to fail throughout the process to produce many of the learning moments for them and teach them how to be resilient. The goal was to have students develop an engineering problem-solving mindset, so that they were comfortable tackling any type of problem that they were presented with. For my high school students, I tried to make sure that the projects I created were challenging but also relevant to their lives. While developing the projects, I tried to think of problems that were going on in their schools or community to ensure they were committed to the work.

I knew that this transition would not be smooth sailing the entire time, but I was comfortable learning as I progressed. I did everything in my power to ensure the class was an overall success for both myself and the students. To further prepare, I made sure that I knew my lessons and materials backward and forward. Every project that I had the students work on, I made sure I knew multiple ways to solve them on my own. The perfectionist in me wanted to make sure I could answer any question that a student may have in relation to the task or at least point them in the right direction. I try to reinforce this preparation for our new instructors. Knowing that everyone isn't a natural born teacher, we try to make sure that they are well versed in the curriculum and receive professional development in pedagogy and classroom management before heading into the classroom. We have found that the more comfortable one is with the material being taught, the better they are able to implement it in front of others.

By Jason Coleman, director of Project Syncere and a member of the committee.

PROFESSIONAL LEARNING EXPERIENCES FOR K–12 TEACHERS OF ENGINEERING

To understand the country's capacity to prepare K–12 teachers of engineering, it is critical to understand the characteristics of professional learning provided to prospective teachers as well as to teachers already working in the classroom.

Programs for Prospective Teachers

The number of teacher preparation programs producing educators equipped to teach engineering is very small, with the largest concentration in the field of technology education. For at least the last two decades, the number of graduates from these programs has steadily declined, from over 800 in the 1995–96 school year to just over 200 in the 2015–16 school year (Moye 2017). The drop in graduates is tied to a loss of preservice education programs: In 2017, there were just 41 such programs (CTETE 2017), compared with 190 programs 10 years earlier (NAITT and CTTE 2007). Ten years ago, a survey of state technology education directors found that there were about 28,000 technology education teachers working in middle and high schools (Moye 2009). That total is comparable to the NTPS estimate of teachers whose primary teaching assignment was in industrial arts or technology education (table 4-3).

It is worth noting that the amount of engineering content in these teacher preparation programs varies, and in some programs prospective teachers are exposed to little or no engineering-related coursework (Fantz and Katioloudis 2011). Research has also found that only about one-quarter of technology teacher preparation programs require coursework in mathematics at the level of calculus or above. Half of programs require at least one physics course, but many institutions allow for the selection of any natural science course to fulfill general education and/or major requirements (Litowitz 2014).

There are no definitive data documenting the impact of the decline in the number of technology educator preparation programs on the supply of these teachers. However, the US Department of Education's Teacher Shortage Areas Nationwide Listing reported 10 states with technology educator shortages in 2016 (Moye 2017). This suggests, at least in these states, that the loss of technology educators due to retirements and attrition is not being met by the supply of newly prepared and credentialed teachers. The American Association for Employment in Education (AAEE) also tracks teacher shortages. In its most recent survey (AAEE 2018), school districts and colleges and universities with education programs indicated "some shortage"[13] of technology educators in the 2017–18 school year. School districts reported the highest shortages in the Rocky Mountain, Middle Atlantic, and Northeast regions. Shortage data from educational institutions indicated that technology educators were in a situation of "medium supply and high demand"; in two earlier periods, 2013–14 and 2015–16, these educators were in "low supply and high demand." The apparent shortages of K–12 technology educators are occurring against a backdrop of potentially significant national teacher shortages in many other subjects, including science (Sutcher et al. 2016).

Another source of potential new K–12 teachers of engineering is programs that allow undergraduate students to combine a major in a STEM field with education coursework and certification to teach. The largest such initiative is the UTeach Natural Sciences program, which started at the University of Texas, Austin, in 1997 and has expanded to 44 universities in 22

[13] Answer choices on AAEE survey items are given numerical values on a 5-point Likert scale. Averages of answer scores from 3.41 to 4.20 were deemed to indicate "some shortage."

states and the District of Columbia. As of 2018 the program had graduated over 4,500 students, nearly 90 percent of whom have become K–12 teachers (UTeach Institute 2018).[14] The majority of these graduates have degrees in science or mathematics; 3 percent have degrees in engineering. Based on data from 2013, 97 percent of graduates of the program obtained STEM teaching credentials. Of these, 44 percent obtained credentials in science, 58 percent in mathematics, 1 percent in computer science, and 0.6 percent in engineering. (Credentialing is discussed in detail later in this chapter.)

Although a small number of UTeach programs have recently enabled engineering students to pair their disciplinary degree with a certificate to teach secondary STEM subjects,[15] UTeach has not caught on in engineering the way it has in the natural sciences and mathematics. One reason may be that starting salaries for engineering majors are higher than any other major except computer science (NACE 2018); thus, the potential loss of income (and reduced ability to pay back a student loan) for following a teacher pathway is one obvious disincentive for engineering students to participate in UTeach. Another is that a typical undergraduate engineering program requires about 130 credit hours (Williamson and Fridley 2017), more than most other degree tracks. Finding time and space in the curriculum for students to take 20 or more education credits and complete student teaching within four years is nearly impossible in most engineering programs. And extending engineering programs to five years to accommodate teacher licensure would raise costs for students.

To address some of the challenges of obtaining a teacher credential while also earning a degree in a very full engineering curriculum, the University of Colorado Boulder, took a different tack. Creating a new degree program in “general engineering” as a starting point, in 2014 the school’s engineering and education colleges crafted a very different design-based engineering program, now called Engineering Plus (E-Plus). E-Plus weaves design- and teamwork-intensive coursework into traditional engineering core theory classes (statics, circuits, thermodynamics, materials science, and data analysis); requires in-depth courses in a traditional engineering discipline (of the student’s choosing); allows a choice of one of 18 “concentrations,” two of which are in secondary school science or mathematics teaching; and integrates interdisciplinary, product design courses throughout all four years. Two of the courses required in the mathematics or science teaching concentration emphasize design: “Project-Based Instruction” in the education curriculum and senior-level “Teaching Design” in the Engineering Plus curriculum.

In 2018 E-Plus enrolled about 140 students, only 8 percent of whom pursued the teaching concentration (J. Sullivan, University of Colorado Boulder, personal communication, August 23, 2018). That year two E-Plus graduates began their teaching careers, and the program was accredited by the Accreditation Board for Engineering and Technology (ABET), the first such program to receive that recognition. Among other things, ABET accreditation means that E-Plus graduates will be eligible to take the Fundamentals of Engineering exam, the first step toward professional licensure. Program leaders believe accreditation may increase the appeal of E-Plus

[14] The UTeach Institute charges fees for schools that want to formally implement the UTeach program. There is an initial, one-time $50,000 curriculum-licensing fee. There are additional costs for support and evaluation services provided during a three-to-five-year initial implementation period. These, along with local implementation costs to start a UTeach program, are generally covered by grant funds or local philanthropy (K. Hughes, UTeach Institute, personal communication, November 11, 2019).

[15] These include Boise State University, Drexel University, University of Alabama, Birmingham, University of Arkansas, University of Colorado Boulder, University of Texas, Austin, and University of Texas, Tyler (K. Hughes, University of Texas, Austin, personal communication, August 23, 2018).

to matriculating engineering students interested in a broad range of concentrations, including teacher licensure.

In addition to the UTeach initiatives, another roughly half-dozen universities across the country provide engineering coursework to students enrolled in teacher preparation programs (some of these are described in NAE and NRC 2014, pp. 122–124). One of the largest is the integrative STEM education program at the College of New Jersey (TCNJ), which is housed in the College of Engineering. It offers two bachelor's of science options for preservice teachers and a master's of education for in-service teachers. The integrative STEM program for preservice K–8 teachers has an enrollment of about 160 and graduates between 35 and 50 teachers per year (Steve O'Brian, School of Engineering, TCNJ, personal communication, August 17, 2018). About 70 percent of these students plan to teach technology education, and they must take seven or eight engineering courses; students who opt for a mathematics or science specialization must take two or three engineering courses. Students in the program's technology and engineering educator preparation track must take 17 courses with engineering content. In the master's program, in-service teachers may follow either a design sequence of courses, which requires six engineering courses, including one on engineering math for educators, or a supervisor certification sequence, which requires students to take the engineering mathematics course and one other engineering course of their choosing. The master's program enrollment is about 35 students, and roughly 30 percent of them are in the design track. Another program is Ohio Northern University's engineering education major, which was established in 2011 and has graduated a small number of secondary-level teachers of engineering. Because Ohio does not offer credentialing for K–12 teachers of engineering, students in the program earn licenses for teaching mathematics (Todd France, Director of Engineering Education, Ohio Northern University, personal communication, July 28, 2019).

Beyond efforts aimed primarily at engineering and technology majors, an important question is to what extent US science teacher education programs incorporate engineering instruction in their curricula, which is relevant given that two-thirds of states have either adopted or adapted the engineering-infused NGSS. The committee could find no research exploring this question directly, but one expert suggested that, in most states, science teacher preparation standards are considerably behind the K–12 academic standards, such as NGSS. As a result, most such teacher preparation programs have not adjusted their curricula to incorporate engineering (personal communication, D. Paulson, Minnesota Department of Education, January 2, 2018). This view is generally consistent with research that finds a considerable gap between current science teaching and the vision for science education presented in NGSS (NASEM 2015).

The National Science Teaching Association (NSTA[16]) and Association for Science Teacher Education (ASTE) recently published new national standards for preservice science teacher preparation programs (Morrell et al. 2019). The standards are expected to be used beginning in 2020, once they are approved by the Council for the Accreditation of Educator Preparation. Reflecting the influence of NGSS and unlike the previous version (NSTA 2012), the new standards address teacher understanding of engineering practices (box 4-3).

BOX 4-3
Engineering-Related Standards and
Elements of 2020 Science Teacher Preparation Program Standards
Standard 1: Content Knowledge

[16] Formerly the National Science Teachers Association (until 2019).

Effective teachers of science understand and articulate the knowledge and practices of contemporary science and engineering. They connect important disciplinary core ideas, crosscutting concepts, and science and engineering practices for their fields of licensure.

Element 1b: Demonstrate knowledge of crosscutting concepts, disciplinary core ideas, practices of science and engineering, the supporting role of science-specific technologies, and contributions of diverse populations to science.

Standard 2: Content Pedagogy

Standard 2: Content Pedagogy

Effective teachers of science plan learning units of study and equitable, culturally-responsive opportunities for all students based upon their understandings of how students learn and develop science knowledge, skills, and habits of mind. Effective teachers also include appropriate connections to science and engineering practices and crosscutting concepts in their instructional planning.

Element 2a: Using science standards and a variety of appropriate, student-centered, and culturally-relevant science disciplinary-based instructional approaches that follow safety procedures and incorporate science and engineering practices, disciplinary core ideas, and crosscutting concepts.

Element 2c: Using engineering practices in support of science learning wherein all students design, construct, test and optimize possible solutions to a problem.

Element 2e: Integrating science-specific technologies to support all students’ conceptual understanding of science and engineering.

Standard 3: Learning Environments

Effective teachers of science are able to plan for engaging all students in science learning by identifying appropriate learning goals that are consistent with knowledge of how students learn science and are aligned with standards. Plans reflect the selection of phenomena appropriate to the social context of the classroom and community, and safety considerations, to engage students in the nature of science and science and engineering practices. Effective teachers create an anti-bias, multicultural, and social justice learning environment to achieve these goals.

Standard 5: Impact on Student Learning

Effective teachers of science provide evidence that students have learned and can apply disciplinary core ideas, crosscutting concepts, and science and engineering practices as a result of instruction. Effective teachers analyze learning gains for individual students, the class as a whole, and subgroups of students disaggregated by demographic categories, and use these to inform planning and teaching.

Element 5a: Implement assessments that show all students have learned and can apply disciplinary knowledge, nature of science, science and engineering practices, and crosscutting concepts in practical, authentic, and real-world situations.

SOURCE: Morrell et al. (2019). Used with permission.

Program leaders involved in preparing prospective teachers of K–12 engineering who were interviewed as part of research conducted for this study by the Education Development Center (EDC) (box 4-4) said there are numerous challenges to accommodating engineering pedagogy in teacher preparation. These include finding space in an already-full curriculum, mustering the political will to change existing programs, and ensuring that there are qualified faculty members to prepare prospective teachers to provide high-quality engineering experiences to their students. Interviewees acknowledged that engineering faculty could fill this role, and this has occurred in many universities. As noted by one program leader,

> [M]any of the schools of education where teachers are prepared…have no clue how to help teachers put engineering into their classes, because they don't have engineers in their faculty. So often, it's faculty in engineering programs [who] find the initiative to do it, thinking about doing some outreach. They start doing weekend programs to engage with teachers around engineering.[17]

BOX 4-4
Survey Research on Pre- and In-Service Preparation of K–12 Teachers of Engineering

To provide additional insights on the state of efforts to prepare K–12 teachers of engineering, the committee commissioned research by the Education Development Center (EDC). The research consisted of a survey of programs that provide engineering-focused professional learning experiences to current and prospective K–12 teachers as well as follow-up interviews with leaders from a subset of these programs. EDC initially identified over 120 programs that met the criterion of including "the explicit instruction of engineering design and/or engineering practices as an explicit goal for the educators, either together with other disciplines or as a standalone discipline." (A description of the methodology used to identify the programs is in appendix 4-A, and the survey instrument and follow-up interview protocol are in appendixes 4-B and 4-C.) From the original set of organizations identified by EDC, 50 completed the survey. Of these, 3 exclusively provided professional learning in engineering to prospective K–12 teachers; 21 provided professional learning to prospective as well as current K–12 classroom teachers; and 25 provided learning experiences to working classroom teachers only. Twenty-one programs served informal educators in addition to prospective or working classroom teachers; two programs served informal educators only.

While some university faculty interviewed by EDC acknowledged the benefit of programs like UTeach, they also described the challenges of infusing engineering into science methods courses for future educators across grade levels, particularly future elementary educators. To create more sustainable and systemic change in teacher preparation, universities cannot rely on the efforts of lone individuals who are passionate about engineering; there needs to be a coordinated effort prioritizing the goal of preparing preservice teachers to integrate engineering into their instruction in a meaningful way. Observed one program leader:

> If we focus efforts to just improve engineering education at colleges of engineering, those places like Purdue are great and they can do a lot to develop programs, but to reach preservice teachers…it has to go beyond colleges of engineering.… But if there is a bigger systemic thing, how are we going to fundamentally change education and get more access to high-quality engineering education?

Professional Development for Current Teachers

There are many more engineering-focused professional development (PD) programs than there are teacher preparation programs, and many more educators are reached by them. A number of these programs are associated with curriculum projects; three of the largest are Project Lead The Way (PLTW), Engineering is Elementary (EiE), and Engineering by Design (EbD) (box 4-5).

[17] To protect confidentiality, EDC anonymized all interviewee quotes.

Other curriculum-based engineering PD programs were described in NAE and NRC (2009), including the Infinity Project, Building Math, INSPIRES, and a World in Motion. A recent meta-analysis of research on improving STEM instructional practices (Lynch et al. 2019) found the greatest impacts on student outcomes were for programs that combined new curriculum materials with professional development.

BOX 4-5
Overview of Curriculum Projects PLTW, EiE, and EbD

Project Lead The Way (PLTW; www.pltw.org) began in New York state in the late 1980s, initiated by a high school technology education teacher. A decade later and supported by a private foundation, PLTW created a high school curriculum that that a number of New York state high schools adopted. It now offers engineering-focused coursework at high schools and middle schools across the United States—over 10,800 in the 2017–18 school year—and in 2014 launched an elementary program. PLTW teachers complete a two-week summer certification program that trains them to deliver the curriculum. Since 1997 more than 52,000 teachers have received this preparation; in summer 2017, more than 13,600 teachers participated. The elementary program, Launch, has trained 18,873 teachers since 2014.

Engineering is Elementary® (EiE; www.eie.org) began in 2003 as a project of the National Center for Technological Literacy at the Museum of Science, Boston. Aimed at elementary students and teachers, EiE units consist of a hands-on engineering design challenge combined with a thematic storybook, teacher guide, and materials kit. The EiE project conducts workshops and other teacher PD activities to support use of the curriculum. Some 11,000 teachers have received EiE and in 2017, based on purchases of its instructional units, EiE estimated that 107,000 teachers were using the curriculum in all 50 states and Washington, DC.

Engineering by Design™ (EbD; www.iteea.org/ebd) is a K–12 curriculum project developed by the International Technology and Engineering Educators Association (ITEEA). Each unit addresses technology and engineering topics and are used primarily by technology education programs in a multistate consortium. ITEEA provides professional development for teachers through its STEM Center for Teaching and Learning, . In 2017, 381 teachers received this professional development, and ITEEA estimates that the curriculum is in use in 30 states by nearly 2,600 teachers in 780 schools.

The 2018 administration of the National Survey of Science and Mathematics Education (NSSME) provides the only national-level data the committee could find that gives a sense of the scale of professional development related specifically to K–12 engineering. One item in the survey asked science teachers whether their professional development over the previous three years gave “heavy emphasis” to a number of areas. Twenty-five percent of elementary teachers, 34 percent of middle school teachers, and 23 percent of high school teachers indicated they had PD to deepen “their understanding of how engineering is done (e.g., identifying criteria and constraints, designing solutions, optimizing solutions)” (Banilower et al. 2018, table 3.10). The NSSME instrument also asked school leaders whether there had been any locally offered PD workshops over the previous three years with “substantial emphasis” in a number of areas.

Thirty-seven percent of schools indicated the availability of PD focused on "How to engage students in doing engineering (e.g., identifying criteria and constraints, designing solutions, optimizing solutions)" (Banilower et al. 2018, table 3.16). The previous administration of NSSME, in 2012, did not include these questions, so it is not possible to know how or whether the prevalence of engineering-focused PD changed during this period. However, data on other measures of K–12 engineering activity, related to the presence of courses, competitions, and clubs (see tables 1-2 and 1-3 in chapter 1), show considerable growth over the six years between the two administrations of the survey.

Returning to the research conducted for the committee by EDC, the sample was quite diverse in terms of geographic focus, number and type of educators served, and duration of PD provided. Forty-seven percent of the programs served the Northeast, 22 percent the Midwest, 20 percent the South, and 12 percent the West; 10 percent of programs served more than one region. In terms of educators served, over 50 percent of programs were quite small, serving fewer than 50 people in 2016; 18 percent served between 51 and 100 people; 16 percent served 101 to 500; and 10 percent served more than 1,000. In terms of duration, nearly 50 percent of programs had 50 or fewer contact hours with educators; 33 percent had between 40 and 100 contact hours; and nearly 15 percent had more than 100 hours.

The survey data are not generalizable because of the small sample size, but they nevertheless provided the committee with a sense of the design, goals, disciplinary focus, and related characteristics of programs providing some form of engineering PD to K–12 educators.[18] In terms of program design, the majority, 54 percent, indicated that the aim was to help educators integrate engineering content into an existing school-based science or mathematics course. Just 10 percent of respondents said their support to educators was related to a standalone engineering course.

In answering an open-ended survey item, programs indicated a broad range of goals, but by far the most common was to improve teacher familiarity with engineering and/or NGSS (table 4-7).

TABLE 4-7 Reported Goals of Engineering-Focused Professional Development Programs (N=46)

	Percent	**Number**
Improve teacher familiarity with engineering and/or NGSS	83	42
Incorporate engineering in their instruction	75	37
Improve science instruction through engineering	70	35
Improve student understanding of engineering	66	33
Develop knowledge of engineering design or engineering practices	40	20
Improve mathematics instruction or understanding	38	19
Enhance comfort, confidence, self-efficacy	30	15
Train teachers as curriculum developers and/or leaders	26	13
Increase/improve college/career opportunities	22	11
Present real-world problem solving, proficiency-based learning	12	6
Increase awareness of equity/focus on all or specific populations	12	6
Create partnerships with industry, community	6	3

[18] Forty-six of the 50 responding programs provided PD in engineering to K–12 teachers (25 did so exclusively and 21 provided both PD and some form of new-teacher preparation). Most of the data collected by EDC and presented here do not separate out responses for teacher preparation and PD programs. When information specific to one type of programs is presented, it is so noted.

Interviews with a subsample of program leaders provided additional details about the program goals and outcomes. Many leaders discussed a primary program goal of increasing teacher and student familiarity with the profession of engineering and roles of engineers. As one described it, “It is about learning the engineering design process and having a better sense of what engineers do.” Overall, programs were designed to expose educators and students to the field of engineering, which many noted is commonly overlooked in K–12 education.

Program leaders saw engineering as a natural hook to promote student learning of mathematics and science. This underlying philosophy was expressed by one program leader: “Children have [a] natural problem-solving inclination” and engineering provides a platform for capitalizing on this ability. Another program leader saw a synergy between engineering, including the NGSS, which infuse engineering, and better content learning: “Robotics is a hook in teaching the standards aligned with the day-to-day science and math these teachers are supposed to do.”

One expressed goal of boosting educator knowledge of engineering was to increase student awareness of, and interest in, careers in the field. Interviewees who described this goal also discussed concerns about equity, such as the importance of offering different types of activities for all students, especially those traditionally underrepresented in STEM, as these quotes illustrate:

> We really want them to understand what engineering is because there is a lot of misinformation about what engineering is and what engineers do. They immediately reach for robotics or Legos and that makes it engineering…. [T]hat tunnel vision does discourage people from going into engineering [who] would be a great benefit to the field…. Girls for, example, may not be attracted to stereotypical robotics like boys.

> If we only present one face of engineering, we will not get as many students interested in it. I do a good job showing it is diverse. It’s diverse in the kinds of problems it tries to solve as well.

In terms of measuring outcomes, the EDC survey found that PD programs for K–12 engineering educators used a variety of methods. The most common was participant surveys, used by 88 percent of initiatives (table 4-8).

TABLE 4-8 Measures of Program Outcomes (N=49)

Method	Number	Percent
Surveys	43	88
Teacher reflections	33	67
Participant interviews/focus groups	32	65
Observations of instruction	31	63
Content knowledge assessment	26	53
External evaluator	22	45
Videos of teacher practice	15	31
No measures used	2	4

Interviews provided additional insights into efforts to assess program outcomes. Some program leaders described efforts to quantitatively measure teacher and student learning of engineering content and skills, as well as teacher comfort with engineering, all of which were primarily measured through surveys or pre-/postassessments. But qualitative measures were more common, in part because they are well adapted to assessing shifts in educator mindset, as illustrated in these quotes:

> We've had a lot of teachers tell us they've fundamentally changed their teaching in general as a result of coming to our workshops, because they've realized they can do open-ended stuff.

> Teachers that participate in our programs do begin to think about teaching differently. They are more enthusiastic and recognize direct instruction is not the only way or the best way, and they do design challenges and begin to write their own. We don't measure them in any scientific way, [but] we do see it.

Interviewees noted that many of the shifts in educator practice that their programs aim to encourage are difficult to document using available tools. K–12 engineering education is relatively new and there are fewer standardized outcome measures. This makes it more difficult for programs to document change, and suggests that there is room for programs to share the tools, procedures, and protocols they develop for their projects. Program leaders noted that it can be difficult to disseminate their findings and tools, and to bring more coherence to the field, because it is hard to publish research on K–12 engineering education. One participant described the challenge this way:

> To get this stuff published, you have a limited number of publications that accept this work: the *Journal of Engineering Education* and the *International Journal of Engineering Education*.[19] But it's really hard when you try to show something that is taking place in a nonengineering classroom. *JEE* editors are critical of that…. [I]f you are trying to do this in science education journals, the science education folks have not warmed up, because they are not OK with engineering in science. You have the old guard in science that really doesn't see this as something that has capacity like science has for a long time.

Program leaders also described the challenges associated with sustaining or growing their initiatives in light of inconsistent or uncertain funding. Many discussed NSF support as instrumental to their programs but also having to piece together a portfolio of projects that address engineering education in a variety of ways. Such efforts may be complementary though not necessarily related, and maintaining programs beyond federal support is challenging. As one interviewee noted:

> We've had different funding streams along the way. It's difficult, now that NSF funding has ceased. The challenge really is how to sustain the program through lesser means.

Some programs have been able to build momentum over the years through strong buy-in among educators, schools, and school districts. To continue to grow, these programs have had to

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[19] Another publication outlet, not mentioned by the interviewee, is the Journal of Pre-College Engineering Education Research (https://docs.lib.purdue.edu/jpeer/),

adapt and change the format and type of support they provide to educators. For example, some larger programs, especially those with national reach, have adopted a "train the trainer" model of professional development, as described by one program leader:

> We had five hub sites around the country, and we trained leaders at colleges and out-of-school organizations. They conducted training.

In summary, a handful of teacher preparation programs include engineering instruction, and the graduates of most of these initiatives end up teaching science or mathematics. In contrast, a considerable number of programs provide engineering-related PD to current K–12 teachers. These vary in their approaches and outcomes, and the reach of most is quite limited.

CREDENTIALING PATHWAYS AND POLICIES

Credentialing is a key element along the professional pathway to a career in teaching. As noted in the statement of task for this study (chapter 1), the committee was asked to examine the mechanisms that are or might be used to recognize expertise and support career pathways for K–12 teachers of engineering. The committee also was charged with considering the practical and policy impediments to effective credentialing options for these educators and how these barriers might be addressed.

Although the NTPS provides a helpful window into the prevalence of certain certifications for several categories of educators who may teach engineering (see "Size of the Workforce" above), it does not provide information about other credentialing options. To understand the credentialing landscape more fully, with help from outside consultants[20] the committee attempted to determine state-level engineering-related requirements for teacher credentialing. (Basic information about teacher credentialing in the United States is provided in box 4-6.)

BOX 4-6
A Credentialing Primer

State departments of education typically issue teacher credentials, often called a license or certification, to individuals who have completed a teacher preparation program. These systems identify both the content knowledge required to be credentialed in a particular subject matter and the formal preparation in pedagogy and other professional knowledge that is required. States articulate these requirements in standards that describe what a teacher should know and be able to do as a professional educator.

Generally, the initial preparation of teachers is associated with a content major through an approved teacher preparation program in an institution of higher education or other sponsoring institution. Often, teacher candidates must complete either an approved major at the bachelor degree level or a required number of credit hours in a specific content area in order to be certified in that area. In addition to completion of an approved professional educator program, states issuing credentials require prospective educators to pass a content area knowledge examination and/or a test to demonstrate competency in pedagogy. These tests may be designed and administered by a third party, such as Educational Testing Service, Pearson, or

[20] The consultants were Michael A. de Miranda, Claude H. Everett, Jr. Endowed Chair in Science and Engineering and department head, and Burhan Ozfidan, postdoctoral research associate, both in the Department of Teaching, Learning and Culture, Texas A&M University.

the College Board, or by the state's department of education. Content in the exams is determined by the state's teaching area content standards or by standards developed by national professional associations or consortiums. Expectations for mastery of content are not uniform across states. In addition, most states allow current or prospective teachers to teach additional subjects, often related to their area of initial licensure, by obtaining what are frequently called endorsements or permits.

A second pathway to teacher certification in STEM areas is through career and technical education (CTE) programs associated with preparation for teaching generally at the secondary level (grades 7–12). Educators in CTE programs must meet the credentialing requirements of the Carl D. Perkins Vocational and Technical Education Act of 2006, federal legislation that provides for funding of the CTE programs, including partial salary remuneration for teachers who hold a CTE teaching credential.

State departments of education credential teachers of CTE largely in the same ways that they credential teachers in other subject areas, although there are some differences with initial teacher preparation requirements. CTE credentialing often offers multiple professional pathways to teacher certification. For example, in lieu of requiring the completion of an approved teacher preparation program at an institution of higher education, CTE credentialing can require a combination of academic preparation and documented professional work experience in the occupational field. The possibility to substitute work experience for academic credentials is evident in the NTPS data (table 4-6).

SOURCE: de Miranda and Ozfidan (2018).

The effort involved a search of the official websites of state departments of education and state CTE programs for the presence of engineering and/or engineering design content (box 4-7), using credentialing terms such as "engineering," "technology education," "STEM," "industrial arts," "engineering and technology education," and "industrial education." The search proved challenging because of states' multiple online locations for storing such information, less-than-optimal navigation and search features on some websites, and inconsistencies in the terminology used.

BOX 4-7
Determining What Counts as "Engineering Content"

De Miranda and Ozfidan used two methods to try to determine whether a teacher credential required knowledge of engineering. First they examined the content of credentialing tests administered by commercial test-development companies, such as Education Testing Service (ETS), Pearson, or McGraw-Hill, or a state's own test. For example, according to ETS, 20 percent of questions in its technology education test (Praxis 5051) focus on "technological design and problem solving," two activities that share strong similarities with engineering. Thus if a credential required ETS test 5051, it was considered to require knowledge of engineering. An example of such a state-administered test is Indiana's CORE assessment in engineering and technology education (#018): the Indiana Department of Education (2012) says 30 percent of its content is related to the "foundations of engineering and technology."

When a specific content test was not specified or a test's engineering content could not be verified, the consultants examined the state's teacher credentialing content standards. If the standards required the credential holder to know about topics such as engineering design, engineering problem solving, engineering physics/sciences, and/or specific engineering disciplines, the credential was considered to address engineering and it was included in the results. For example, in Iowa, for a teaching endorsement in 5-12 Engineering (#974), candidates must have had 24 semester hours of engineering coursework (IBEE 2019).

The most common credential, available in 27 states, was for "technology education." This is not surprising, given the long history of that field in US education and its turn toward engineering over the past two decades. As noted above ("Programs for Prospective Teachers"), teacher preparation in the field of technology education is in decline.

These states require prospective technology teachers to pass the ETS Praxis 5051 exam, which is based in part on the *Standards for Technological Literacy: Content for the Study of Technology* (*STL*; ITEEA 2007). *STL* calls for students to develop an understanding of the attributes of technological and engineering design (see tables 2-2 and 2-3). The test specifications for this area of the exam, shown in box 4-8, emphasize design and concepts such as optimization, modeling, and prototyping that are central to engineering work, but do not mention engineering. A number of other states require the Praxis 5051 for credentials with names similar to technology education, such as "engineering and technology education" (e.g., Florida, Georgia, Idaho), "industrial technology" (e.g., Arkansas, Illinois, Montana), and "engineering technology" (e.g., Hawaii, New Jersey, South Carolina).

BOX 4-8

Permission Pending

A small number of states include engineering requirements in credentials for STEM teachers. Colorado, for example, offers a STEM endorsement for secondary grades through its CTE program that can be satisfied by taking a number of STEM-related college courses, including in engineering (although engineering coursework is not required) (Colorado Department of Education 2016). Teachers can bypass the course-taking requirement if they have an independent certification, such as that of Project Lead The Way for its high school engineering curriculum.

Work experience or a national industry license or certification can also meet the content knowledge requirement for STEM teaching certification, as can passing three Praxis tests, in mathematics, science, and technology education. In Iowa, teachers in grades K–8 can get a STEM endorsement that allows them to teach science, mathematics, or "integrated STEM" (IBEE 2019). The endorsement requires significant coursework in science and mathematics as well as a minimum of three credit hours in content or pedagogy of engineering and technological design.

A number of states offer specialized CTE credentials across a range of technical topics, including engineering. For example, Arkansas grants permits in preengineering, career–aerospace engineering, career–biotechnical engineering, career–civil engineering and architecture, and career–engineering design and development (Arkansas Department of Education 2016). Under a CTE category called "engineering and science technology" (separate from technology education), Ohio offers licenses in engineering technology design, engineering technology process, and engineering technology products/services (Ohio Department of Education 2017).

With the understanding that what gets measured is often what gets taught, the committee examined a sample of state certification tests for the amount and type of engineering content. Some states put relatively little emphasis on engineering in their tests. For example, just 10 percent of multiple-choice items in Florida's Teacher Certification Examination for engineering and technology education is devoted to "knowledge of principles of engineering" (Pearson Education 2018). Teachers who demonstrate this knowledge should be able to

- identify appropriate design and problem-solving principles and procedures in engineering design,
- analyze factors involved in engineering design (e.g., economic, safety, ergonomic, reliability),
- analyze data acquisition methods in engineering (e.g., the use of test equipment, measurement instruments, research techniques), and
- analyze legal and ethical issues in engineering.[21]

In Georgia, a much larger share of questions in the certification test for engineering and technology education is devoted to engineering topics. Of six areas on the test, three—Engineering Design and Application, Engineering Profession and Professional Growth, and Design and Modeling, accounting for roughly half of the assessment's questions—have clear connections to engineering (ETS 2016). Test takers should be able to demonstrate that they

- understand the engineering design process;
- know how to apply and use engineering principles in the engineering design process;
- understand the organizational structure and history of engineering and career education and practice and how it relates to American business, industry, and careers; and
- can determine the selection and application of tools to gather, evaluate, validate, and use information.[22]

[21] See www.fl.nesinc.com/studyguide/FL_SG_obj_055.htm, Competency 3.
[22] The "knowledge statements" associated with this objective are: Identifies the attributes of design, Evaluates the results of the engineering design process, and Uses and analyzes modeling and prototyping.

Texas is one of the few states that has credentialing for teachers of engineering outside of CTE. Although embedded in a combined teaching area—mathematics/physical sciences/engineering (8–12)—the engineering standards for teachers opting for this certification are ambitious (TSBEC 2004), as are the competencies based on them, which are the basis for the state certification exam (Texas Education Agency 2011). Nearly a third of test items—in two domains, the Engineering Method and the Engineering Profession—focus on engineering. (The Texas competencies are discussed in greater detail in chapter 5, "Engineering Content and Practices.") Competencies in the two domains include:

- A working knowledge of engineering fundamentals (e.g., principles related to statics, dynamics, electric circuits, fluid mechanics, thermodynamics, control systems)
- Understanding of the role of mathematics, science, and economics in the design process (e.g., application of knowledge of a variety of mathematical topics, including trigonometry, vectors, matrices, and calculus to solve engineering problems
- Understanding of the engineering design process, including using technology to to test design solutions and, based on that analysis, redesigning products, systems, or services.

In summary, the qualitative and nonuniform nature of the data collected about credentialing limits the committee's ability to draw conclusions. It appears clear, however, that technology education is the most common engineering-related pathway at the state level for K–12 teachers. Many fewer options exist to demonstrate engineering expertise for credentialing. It is equally clear that there is considerable variance among states, and even within states, regarding expectations for teachers' engineering knowledge. This can readily be seen by comparing the scope of the Praxis 5051 exam with the more demanding engineering competencies expected of educators who seek to obtain the Texas credential in mathematics/physical sciences/engineering.

Beyond the analysis of the NTPS data, the committee was unable to determine how many people have received other types of engineering-related credentials. Efforts by de Miranda and Ozfidan to collect such information from state departments of education proved fruitless. Nevertheless, we infer from other indicators, such as the paucity of teacher preparation programs in this area, that there are relatively few K–12 teachers with engineering-related credentials other than those in technology education.

The committee's difficulty determining certification options in K–12 engineering suggests that awareness of these options among prospective teachers and teacher educators is likely quite low. The research conducted by EDC probed awareness of state credentialing policies related to K–12 engineering among the 50 programs included in its survey: respondents were able to identify 11 states they thought had such policies, but over half (55 percent) indicated that they did not know or were unsure whether such policies existed.

CONCLUSION

The committee's effort to determine the size and composition of the workforce of K–12 teachers of engineering in the United States was hampered by limitations in the available data. Even taking these constraints into account, one troubling data point is the preponderance of white males that appears to be working in this domain. It was not difficult to identify programs that provide some form of professional development to current classroom teachers, but it was not possible in most cases to assess their effectiveness; the reach of most of these programs is limited. There are very few postsecondary programs preparing new teachers to teach engineering, and most of these are in technology education. The credentialing landscape for K–12 teachers of engineering is hard to chart; a number of state credentials reference engineering, but it is not clear that any provide a professional pathway into teaching engineering at the K–12 level.

Despite the call in NGSS for K–12 science teachers to connect engineering ideas and practices with those of science, the committee found little evidence that current science teachers are doing so or that prospective science teachers are being given the opportunity to gain engineering knowledge as part of their preparation to enter the classroom. College engineering course taking among science teachers is low across K–12, but it is particularly low for elementary teachers. It is somewhat encouraging that in the sample of engineering-related PD programs surveyed by EDC, over half aimed to help teachers integrate engineering content into an existing school-based science or mathematics course.

Whatever the challenges associated with describing the current workforce of K–12 teachers of engineering, it will be important to provide high-quality, effective professional learning experiences to these educators. To this end, chapter 5 presents what we know about the professional learning needs of teachers generally and of K–12 teachers of engineering specifically, and describes some of the program characteristics important to meeting those needs. Chapter 6 considers a number of factors in the larger education system that will play an important role in ensuring the availability of quality professional learning opportunities in engineering for current and prospective K–12 teachers.

APPENDIX 4-A: EDC DATA COLLECTION METHODOLOGY

This study and our data sources were guided by frameworks such as *Standards for Preparation and Professional Development for Teachers of Engineering* (Farmer et al. 2014; Reimers et al. 2015) and Brown and Borrego's (2013) review of NSF-funded MSP engineering projects. These documents helped to inform the specifics of what the committee might look for in engineering educator preparation and professional development programs, and later provided a scheme for categorizing findings. In an effort to build on our understandings from these documents and our prior work, the study began with several meetings with project advisors, including informal interviews with two experts who lead engineering education programs. The purpose of these interviews was to identify survey participants and to revise and refine the topics of focus for our survey.

In collaboration with NAE staff, through the conversations with advisors and experts and an initial scan of websites and project abstracts, our team developed key program characteristics that provided a framework for building survey items. The resulting survey consisted of several sections of questions that asked respondents to describe their programs: program background, professional development goals and outcomes, and program structures and activities. Survey items also asked about reflections from across the field of educator preparation as it relates to preK–12 engineering education.[23] The survey contained approximately 40 questions; question-

[23] The survey methodology and resulting survey instrument refer to *pre*K-12 education, because they were developed before the committee decided to limit the focus of its data gathering and analysis to grades K-12.

item formats were a mix of multiple choice (respondents choose one answer), Likert (scale), multiple answer (respondents choose multiple answers), and open-ended (text box). The full survey is included in appendix 4-B.

Feedback on the survey constructs provided during the initial meeting of the committee, followed by conversations with NAE staff, informed not only the development of survey constructs and items but also the determination of inclusion criteria. Specifically, our sources informed our definitions of educators, professional development programs, engineering focus, and other criteria (see table 4-A-1).

TABLE 4-A-1 Inclusion Criteria

Who are the educators?	Formal and informal educators who provide direct instruction to preK–12 students in school classrooms, afterschool programs (e.g., Boys and Girls Club, 4-H), or informal environments, such as museums or other science/technology education centers. *This does not include* instructional coaches (unless they also fit the educator description above), school or district administrators, school board members, or undergraduate educators.
What constitutes preparation/professional development?	Educator support that uses, develops, or tests a specified professional development model that may not accompany a specific curricula, and includes ▪ online, in-person, or blended "meetings" (e.g., institutes, workshops, webinars, online courses). ▪ credentialing, credit, professional development points, informal badging mechanisms, or other outcomes that recognize the participation of the educators. *This does not include* ▪ programs that focus solely on developing educational interventions and/or provide only informal support for educators (e.g., website materials, teacher guides, or references to accompany kits). ▪ support for teachers in order to develop or test a specific curricula.
What is the engineering focus?	Programs that include the explicit instruction of engineering design and/or engineering practices as an explicit goal for the educators, either together or with other disciplines, or as a standalone discipline.
Other criteria	We will identify programs that are currently operating and are focused on supporting educators in the United States. Those focused on international educators and/or those not currently operating will not be included. We will not include programs where we cannot determine details above from abstracts, interviews, and other original sources, we will not include the program (e.g., lack of contact person, vague details provided on an abstract).

Our scan of websites and abstracts enabled our team to also identify potential survey respondents. Our scans resulted in an initial list of over 80 programs, with information about websites and key personnel who could respond to our survey. Survey items were programmed into Qualtrics. For programs that met our inclusion criteria, a link to the surveys was sent by email to key personnel, with a message from the project team briefly describing the study, the criteria by which they were selected to participate, and a link to the survey. Participants were given a window of approximately four weeks from late January through late February 2017 to complete the survey. Reminder messages were sent to participants once a week. Out-of-office email replies were noted by the project team, and participants who were unavailable by email were sent reminder emails at the time when they were available. For emails that bounced back, when possible a second potential respondent was identified for the same program and a survey was sent to this backup respondent. In four cases, we received a bounce-back and a backup respondent was unable to be identified.

To increase our pool of respondents, we included a question on the survey asking respondents to refer us to other programs and colleagues who might fit our inclusion criteria. Therefore, the survey was sent in two waves: the first wave went to 72 respondents whom we had identified through our reviewed sources as meeting our inclusion criteria; the second wave, sent two weeks later, went to an additional 51 respondents identified through respondents to the first wave, for a total of 123 possible respondents. During the week prior to closing the survey, the project lead sent one final, more personal follow-up email, briefly describing the importance of the survey and stating the closing date. At the end of the two waves of survey administration, we received a total of 50 survey responses that met our inclusion criteria, representing a response rate of 42 percent. Characteristics of the programs represented by these survey responses are described in the results section.

Follow-up interviews were conducted with program leaders who responded to the survey. Our goal in conducting these interviews was to gather more in-depth information about programs that have the potential for a large impact and to understand the perspectives of individuals who run these programs on the opportunities and gaps across the field. Given these goals, we used several strategies to identify participants in these interviews. First, we identified programs by impact (those reaching 100 or more educators in 2016) based on their survey responses, duration (offering instructional support to educators for five or more years), and geographic focus and reach. Additional "experts" to interview were identified using a snowball approach, asking internal and external advisors, as well as other participants in these follow-up interviews, to identify others with knowledge across the field. If the identified participants had not already participated in the survey, we invited them to do so before participating in the interview. Finally, in selecting interview participants for follow-up interviews, we ensured representation of a variety of programs—for preservice and in-service teachers, providing formal and informal education, and addressing different grade levels and disciplines. We conducted 12 follow-up interviews.

Interview questions addressed the main categories of interest covered in the survey but probed for more descriptive information about the categories from the survey (background, structures, outcomes, and challenges and opportunities across the field) in addition to broader commentary on the field. The program background questions gathered additional information from the program leaders around program design and processes. For example, with respect to the program design, questions included "What are the goals of your work with educators?" and "How does your program define engineering design, and how is this communicated to educators in program activities?" The interviews also probed for more information about the research base underlying the respondents' approach to their work with educators ("What research did you draw upon to develop this approach?").

With respect to program structures, the interview questions emphasized understanding program processes, particularly how the program goals around engineering were communicated to, and experienced by, participating educators. Toward this end, questions requested information about what educators experience in a professional development session to get a sense of the strategies and learning experiences used to support educator learning of the practices of engineering.

This attention to process was also the goal of the interview questions on outcomes. Questions asked not only how they assess the effectiveness of the professional development offered to educators but how they use these findings to inform their work. For example, "What are the strengths of your program?" "What are areas for improvement?" and "How has your program changed over time?"

In the final section of the interview, we asked participants to offer their perceptions of challenges in preparing educators to teach engineering, and more broadly the challenges for the field and opportunities for expanding educator preparation. All interviews were audio-recorded and transcribed for analysis.

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APPENDIX 4-B: EDC SURVEY

Introduction

Education Development Center (EDC) has been contracted by the National Academy of Engineering (NAE) to conduct a landscape analysis of engineering education. The goals of the study are to describe existing efforts that support educators' instruction of engineering and explore possible gaps and opportunities for supporting engineering instruction.

Purpose

The purpose of this survey is to gather descriptive information regarding characteristics of engineering education programs that provide services for educators, whether for preservice or in-service educators in either formal (preK–12) or informal learning environments (e.g., out-of-school programs).

Your Role

You are receiving this survey because you have been identified as someone who leads, directs, coordinates, or has knowledge of a project or program that includes the preparation of educators to teach engineering. This survey will ask you to describe various elements of the program and/or project(s) that you are affiliated with and should take approximately 15 minutes to complete.

Confidentiality

Your responses will be kept confidential and individuals who respond will not be shared with NAE. While the survey does ask for your name and affiliated program, this is done for tracking purposes only. Your participation in this survey is greatly appreciated, as it will contribute to an understanding of the current status of efforts across the country to prepare educators to teach engineering at the preK–12 level. Some self-selected respondents will be asked to participate in a follow-up interview in order to understand individual programs in more depth. If you have any questions about this survey, please contact Jackie DeLisi at jdelisi@edc.org.

Questions about You

We are interested in hearing about the engineering education program or project that you are most familiar with. If you work with more than one program or project, please choose the one that you are most involved in to respond to the questions below.

First Name (1)
Last Name (2)
Organization (3)
Title/Position/Role (4)
Program Name (please enter the name of the program you are most involved in) (5)
Program website address (6)

Program Overview

Does your program provide professional development (PD) or training to teachers? For the purposes of this survey, when we refer to PD, we mean support for either current or future educators that is using, developing, or testing a specified professional development model, and includes (1) online, in-person, or blended "meetings" (e.g., institutes, workshops, webinars, online courses) AND (2) credentialing, credit, professional development points, informal badging mechanisms, or other outcomes that recognize the participation of the educators. Note that PD can be intended for either preservice teachers, in-service, or both.

❍ Yes (1)
❍ No (2)
❍ Unsure (3)

Please check all that apply. Does your program provide support to:

❑ Current educators of PK–12 classrooms (1)
❑ Future educators of PK–12 classrooms (2)
❑ Current educators of PK–12 students in informal settings (3)
❑ Future educators of PK–12 students in informal settings (4)
❑ None of the above (6)
❑ Other (please specify): (7) ____________________

Does your PD support educators in their knowledge of, and ability to teach, the engineering design process and/or engineering practices?

❍ Yes (1)
❍ No (2)
❍ Unsure (3)

Program Background

For how many years has your program included support for engineering instruction?

- ❍ 0–3 years (1)
- ❍ 3–5 years (2)
- ❍ 5–7 years (3)
- ❍ 7–10 years (4)
- ❍ More than 10 years (5)

Who provides the PD? (Please check all that apply.)

- ❑ College or university (1)
- ❑ Industry (2)
- ❑ Nonprofits (3)
- ❑ Other (please specify): (4) ____________________

What is the grade level focus of educators in PD? (Please check all that apply.)

- ❑ Pre-school/Kindergarten (1)
- ❑ Elementary (2)
- ❑ Middle (3)
- ❑ High (4)
- ❑ Other (please specify): (5) ____________________

How is the PD provided?

- ❍ In-person (1)
- ❍ Online or through video (2)
- ❍ Blended (3)
- ❍ Other (4)

What is the locale/geographical focus of PD? Please enter all states where PD is provided in the text box below.

Are the teachers expected to teach engineering as:

- ❍ As a standalone course in a school (1)
- ❍ Integrated in a preexisting school-based science or math course (2)
- ❍ Embedded in other non-STEM courses in schools (3)
- ❍ As part of an afterschool or informal math or science program (4)
- ❍ As a standalone engineering-focused program in an afterschool or informal setting (5)
- ❍ Other (please specify): (6) ____________________

How many educators participated in your engineering PD in 2016?

How many educators have participated, in total, throughout your program's history?

Does your program involve educators from formal and informal settings?

- ❍ Formal (1)
- ❍ Informal (2)
- ❍ Both (3)

If both, approximately how many educators have you reached in the past year from:
Formal Settings: (1)
Informal Settings: (2)

What is the dosage of your PD? (duration, # of contact hours, etc.)
Duration:
Number of contact hours:

How do participants find out about your program?
Does the program have industry partnerships? Other partners?
- ❍ Yes (1)
- ❍ No (2)

Please list your partners.

Professional Development Program Goals and Outcomes

What are the top three goals of your engineering-focused PD?
1:
2:
3:

As a result of participating in your engineering PD, what do you anticipate educators know or are able to do? *(Examples: teachers report increased comfort; teachers able to implement engineering activities according to our framework; teachers understand engineering design)*
What types of measures do you use to determine these educator outcomes? (Please check all that apply.)
- ❑ Survey of participants (1)
- ❑ In-person observations of educators working with students (2)
- ❑ Observations of the PD sessions (3)
- ❑ Interviews/focus groups with participants (4)
- ❑ Assessment of content knowledge (5)
- ❑ Videos of teacher practice (6)
- ❑ Teacher reflections (7)
- ❑ Our PD program employs an external evaluator (8)
- ❑ We have not yet developed measures of success (9)
- ❑ Other (please specify): (10) ____________________

What additional methods, if any, do you use to document your program's success?
What incentives do you offer teachers? (Please check all that apply.)
- ❑ Licensure (1)
- ❑ Credentialing (2)
- ❑ Badging (3)
- ❑ Course credit (4)
- ❑ Teacher PD hours (PDP) (5)
- ❑ None (6)
- ❑ Stipends or honorariums (7)

- ❑ Curricular and/or instructional resources (8)
- ❑ Access to an online resources (platform) (9)
- ❑ Other (please specify): (10) ____________________

What engineering education credentialing, if any, is offered in your state?

Program Activities

Does the program have an explicit connection to a specific curriculum?

- ❍ Yes (1)
- ❍ No (2)
- ❍ Unsure (3)

Please provide the name of the curriculum for which your PD program has a connection to:

Does your engineering PD program make specific connections to other disciplines?

- ❍ Yes (1)
- ❍ No, PD is only focused on engineering (2)
- ❍ Unsure (3)

What is the primary disciplinary focus of the program?

- ❍ Primary focus on math with engineering incorporated (1)
- ❍ Primary focus on science with engineering incorporated (4)
- ❍ Primary focus on engineering (2)
- ❍ Other (please specify): (3) ____________________

Please indicate which other disciplines your PD program connects to:

- ❑ Science (1)
- ❑ Math (2)
- ❑ Technology (3)
- ❑ Computer Science (4)
- ❑ Language Arts (5)
- ❑ Social Studies (6)
- ❑ Other (please specify): (7) ____________________

How important is it that your PD provide each of the following: (see next page for question)

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Hands-on engagement by the educators in engineering activities (1)	❍	❍	❍	❍	❍
Educators examine student work (2)	❍	❍	❍	❍	❍
Educators practice teaching engineering activities with students (3)	❍	❍	❍	❍	❍
Educators observe others teaching engineering activities (4)	❍	❍	❍	❍	❍
Educators collaborate with others from the same schools and districts (5)	❍	❍	❍	❍	❍
Educators come from a variety of disciplines (6)	❍	❍	❍	❍	❍
Educators learn about an explicit engineering model (7)	❍	❍	❍	❍	❍

Educators are provided with activities that are aligned with the Next Generation Science Standards (8)	❍	❍	❍	❍	❍

Across the Field

This section of the survey asks about your understandings and reflections from across the field of educator preparation as it relates to preK–12 engineering education.

1. Please list any other programs or projects that you know of that train educators in engineering:
(Examples: programs based at institutions of higher education, nonprofits, museum settings, or industry; programs based on school level partnerships)

2. Which, if any, of the programs that you listed above prepare educators to teach a standalone engineering course where the primary goal is to teach engineering?

3. Which states are you aware of that provide licensure and credentialing in engineering education?

4. Thinking about your knowledge and experiences within the field of engineering education, what are some of the greatest challenges facing engineering education pre- and in-service programs?

5. If an educator asked for advice on how to learn how to teach engineering, what programs (preparation or professional development) would you recommend?
If an educator asked for advice on how to learn how to teach engineering, what pathways (e.g. formal licensure or credentialing, certificates, etc.) would you suggest for becoming an engineering educator?

6. Is there anything else you think we should know about your engineering-focused PD?

7. Is there anything else you think we should know about the field of engineering educator preparation more broadly?

We will be conducting follow up interviews in order to understand programs in more depth. Would you be interested in participating in a follow-up interview?

❍ Yes (1)

❍ No (2)

Thank you for your interest. What would be the best way to contact you for scheduling an interview?

Email (please provide preferred email):

Phone (please provide preferred number):

Would you be able to refer our team to a colleague that would be interested in participating in an interview? (If not, please leave this text box blank.)

APPENDIX 4-C: EDC FOLLOW-UP INTERVIEW PROTOCOL

Thank you for taking the time to speak with me today. My name is [Name of researcher] and I work for Education Development Center (EDC), a nonprofit organization located in Waltham, MA. EDC has been contracted by the National Academy of Engineering (NAE) to conduct a landscape analysis of preservice and in-service engineering education in order to explore possible gaps and opportunities that exist with regard to supporting educators' instruction of engineering programs that support educators' instruction of engineering in formal and informal education settings for students in grades Pre–K to 12. We are gathering this information through surveys and follow-up interviews with program directors. We identified your program for participation in this follow-up interview because of the reach and longevity of your program. The purpose of this interview is to gather more in-depth descriptive information about your program and to identify potential successes and gaps for engineering education as a field. The interview questions fall into four main categories including the background of your program, program structures, outcomes, and across the field.

This interview should take approximately 45 minutes to an hour. You do not need to answer all of the questions asked, and we can stop the interview at any time. With your permission, I would like to audio record this conversation. If you have any questions about this study, please contact Jackie DeLisi, project director at jdelisi@edc.org.

Do you have any questions for me before we begin?

Background

1. Tell us more about your program.
    a. What problem was your program designed to address?
    b. How long has your program been operating?
2. What are the goals of your work with educators? Of the professional development (PD) specifically?
    PROBE: Implement "kit" or standalone unit? Change practice? Implement design thinking?

3. We know your program focuses on engineering. Can you describe the role of engineering on your program? How is engineering connected to other disciplines?
    PROBE: Primary focus on engineering or integrated with math/science/literacy?
4. How does your program define "engineering design"?
    a. How is engineering design represented in your program activities?
    b. How is engineering design communicated to educators through PD?
5. What is the underlying theoretical framework guiding your program? What are the assumptions that guided the development of your PD?
    a. How was this developed?
    PROBE: What resources/reports did you refer to? What other programs did you rely on?
    b. How does your theoretical framework inform the support you provide to educators? Your model of PD?

Structures

6. Describe what participants experience in a typical PD session.
    a. What are some of the important features of your PD? What do you feel strongly about? PROBE: active engagement, observing or practicing in classrooms, how they meet, who leads it
    b. To what extent does PD involve participants in active engagement in engineering activities?
    c. To what extent do programs involve participants in observing or practicing in classrooms?
    d. How often do participants meet? How do they meet?
    e. Who leads the PD?
7. How is your PD connected to NGSS, if at all? NGSS and your PD?

   a. How is this connection made?
   b. What changes have you made to your PD in response to NGSS
8. On the survey, we asked if your program has any partners. What support do your partners provide the program?
   a. How do partners support your work with educators in PD?
9. In what ways, and to what extent does the program involve educators working in formal and informal learning environments?

Outcomes

10. How do you assess the effectiveness of your PD?
    a. What types of outcomes, if any, does your program document?
    PROBE: changes in beliefs, attitudes, and knowledge, and/or teaching practice
    b. What have you learned from these assessments?
11. In general, what are the strengths of your program?
    a. What are the areas for improvement?
12. In what ways has your program changed over time? What have you done with any of the results of the outcomes you measured?
    a. Why? What prompted those changes?

Across the Field

13. What gaps do you see in engineering education as a field?
    a. Why do you think these gaps exist?
14. What opportunities exist in engineering activities as a field? What trends do you see? Where do you see potential for continuing to expand or improve preparation for engineering instruction?
15. Is there anything else you think is important for us to know about your program that we haven't discussed today?
16. Why do you think we should talk to them?

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5

Professional Learning

The goals for teaching engineering in US classrooms are both ambitious and varied, but, as explained in chapter 4, the majority of K–12 educators do not currently teach engineering and have little preparation to do so. Whether they are to teach for engineering literacy, integrate engineering in STEM education more generally, prepare students to be college and career ready, or educate future engineering majors, teachers will need certain knowledge and skills as well as opportunities to acquire those competencies. This chapter explores two questions:

1. What are teachers' *learning needs* for teaching engineering?
2. What *learning opportunities* will teachers require to meet those needs?

The first question explores the professional knowledge and skills built from and for teaching. The second focuses on the opportunities for teacher learning that lead to the development and growth of the knowledge and skills. The committee sought evidence related to both questions.

LEARNING NEEDS FOR TEACHING ENGINEERING

To understand the potential learning needs of K–12 teachers of engineering, we begin by looking at what researchers believe are important learning needs of K–12 teachers generally, which has been the focus of considerable scholarship, analysis, and policymaking. In part this is because of the assumed causal connections between specific aspects of professional knowledge, teaching behaviors, and student outcomes. Unfortunately, there is little consistent evidence that elementary teachers need specific mathematical knowledge or that science teachers who use a particular instructional strategy always produce learning gains in students (e.g., NRC 2010). This may be because a great deal of research on teaching and learning focuses on singular aspects of education, whereas teachers work on multiple fronts at once. Alternatively, the contextual, situated nature of teaching and learning may thwart efforts to identify simple causal connections.

Nonetheless, various groups have attempted to delineate what K–12 teachers need to know and be able to do, with the belief that certain approaches are more likely to lead to student success than others. These efforts include handbooks (e.g., Cochran-Smith and Zeichner 2005; Darling-Hammond and Bransford 2005); state and professional organization standards for teachers (e.g., NBPTS 2016; NCTM 2017; NSTA 2012); the content of teacher preparation and professional programs, teacher licensure, and certification examinations (e.g., Praxis content knowledge and teaching examinations); teacher development and evaluation systems (e.g., Danielson 2014); teacher assessments developed for research purposes (Ball et al. 2008; Hill and Ball 2004; Hill et al. 2004); and teacher and program accreditation and teacher certification requirements. Across these different documents and contexts, teacher knowledge and skill are parsed in different ways.

It was beyond the scope of the committee's work to synthesize the many different conceptualizations of teacher learning needs. However, readers may benefit by seeing two better-known efforts to define the body of knowledge for K–12 educators. The Danielson (2014) Framework (box 5-1), the basis for a widely used teacher development and evaluation system, parses teacher professional knowledge into four domains with 22 subdomains that are further subdivided into 76 smaller elements. The framework is based on logical analyses of what the work of teaching entails, a broad reading of relevant research, and feedback from educators across the country who have used various iterations of the document. Notably, the framework is subject-matter agnostic; that is, its guidance is independent of the subject taught.

BOX 5-1
Danielson Framework

Domain 1: Planning and Preparation
- 1a. Demonstrating Knowledge of Content and Pedagogy
- 1b. Demonstrating Knowledge of Students
- 1c. Setting Instructional Outcomes
- 1d. Demonstrating Knowledge of Resources
- 1e. Designing Coherent Instruction
- 1f. Designing Student Assessments

Domain 2: Classroom Environment
- 2a. Creating an Environment of Respect and Rapport
- 2b. Establishing a Culture for Learning
- 2c. Managing Classroom Procedures
- 2d. Managing Student Behavior
- 2e. Organizing Physical Space

Domain 3: Instruction
- 3a. Communicating with Students
- 3b. Using Questioning and Discussion Techniques
- 3c. Engaging Students in Learning
- 3d. Using Assessment in Instruction
- 3e. Demonstrating Flexibility and Responsiveness

Domain 4: Professional Responsibilities
- 4a. Reflecting on Teaching
- 4b. Maintaining Accurate Records
- 4c. Communicating with Families
- 4d. Participating in the Professional Community
- 4e. Growing and Developing Professionally
- 4f. Showing Professionalism

SOURCE: Danielson (2014). Reprinted with permission. Copyright. 2014. All rights reserved.

Sykes and Wilson (2015), in their review of research on teaching, nominate two domains of professional knowledge with a number of associated subdomains (table 5-1). Like Danielson, this framework is subject-matter agnostic.

TABLE 5-1 Sykes and Wilson Framework

Domain I: Instruction	Domain II: Professional Role Responsibilities
Planning	**Collaborating with other professionals** ✓ Using professional networks

✓ Preparing and planning for high quality instruction ✓ Drawing on students' cultural, family, intellectual, and personal experiences and resources ✓ Promoting community participation as opportunity to explore core values ✓ Setting long- and short-range learning goals and objectives ✓ Mastering lesson content for instructional purposes ✓ Selecting and adapting resources for use in instruction ✓ Selecting/designing instructional tasks, activity structures, and formats ✓ Planning assessments	✓ Communicating professionally, both in person and via technology ✓ Collaborating in professional learning communities and on teams ✓ Exercising leadership, both formally and informally
Relational aspects ✓ Attending to relational aspects of instruction ✓ Developing caring and respectful relationships with individual students ✓ Attending to and promoting student social and emotional needs and learning ✓ Building positive classroom climate	**Working with families and communities** ✓ Fostering two-way, respectful communication with parents and guardians ✓ Using family- and community-related information as a resource for learning
Social/academic life ✓ Establishing and maintaining the social and academic culture ✓ Implementing organizational routines, norms, strategies, and procedures to support a learning environment ✓ Managing the physical and material environment ✓ Managing instructional groupings ✓ Using time productively	**Fulfilling ethical responsibilities** ✓ Enacting the basic moral principles and duties associated with the role of teacher and exercising diligence and prudence in observing these duties ✓ Responding to ethical dilemmas with sound reasoning and actions ✓ Detecting and correcting biases of various kinds via reflection and feedback ✓ Advocating appropriately for students
Interactive teaching ✓ Attending to instructional purposes ✓ Enacting instructional tasks and activities ✓ Engaging students with subject matter ✓ Orchestrating productive discourses ✓ Providing strategy instruction ✓ Assessing and responding to student learning during instruction	**Meeting legal responsibilities** ✓ Complying with all relevant laws and regulations ✓ Creating and maintaining accurate records of student progress and related matters
Improvement ✓ Engaging in instructional improvement ✓ Improving instructional routines ✓ Engaging in deliberate practice	

SOURCE: Sykes and Wilson (2015). © 2015 Educational Testing Service. Reprinted by permission of Educational Testing Service, the copyright owner. All other information contained within this publication is provided by National Academies Press and no endorsement of any kind by Educational Testing Service should be inferred.

The Interstate Teacher Assessment and Support Consortium (InTASC) model core teaching standards and learning progressions offer yet another, similar conceptualization (box 5-2).

BOX 5-2
InTASC Core Teaching Standards

The Learner and Learning
Standard 1: Learner Development—The teacher understands how learners grow and develop, recognizing that patterns of learning and development vary individually within and across the cognitive, linguistic, social, emotional, and physical areas, and designs and implements developmentally appropriate and challenging learning experiences.
Standard 2: Learning Differences—The teacher uses understanding of individual differences and diverse cultures and communities to ensure inclusive learning environments that enable each learner to meet high standards.
Standard 3: Learning Environments—The teacher works with others to create environments that support individual and collaborative learning, and that encourage positive social interaction, active engagement in learning, and self motivation.

Content
Standard 4: Content Knowledge—The teacher understands the central concepts, tools of inquiry, and structures of the discipline(s) he or she teaches and creates learning experiences that make the discipline accessible and meaningful for learners to assure mastery of the content.
Standard 5: Application of Content—The teacher understands how to connect concepts and use differing perspectives to engage learners in critical thinking, creativity, and collaborative problem solving related to authentic local and global issues.

Instructional Practice
Standard 6: Assessment—The teacher understands and uses multiple methods of assessment to engage learners in their own growth, to monitor learner progress, and to guide the teacher's and learner's decision making.
Standard 7: Planning for Instruction—The teacher plans instruction that supports every student in meeting rigorous learning goals by drawing upon knowledge of content areas, curriculum, cross-disciplinary skills, and pedagogy, as well as knowledge of learners and the community context.
Standard 8: Instructional Strategies—The teacher understands and uses a variety of instructional strategies to encourage learners to develop deep understanding of content areas and their connections, and to build skills to apply knowledge in meaningful ways.

Professional Responsibility
Standard 9: Professional Learning and Ethical Practice—The teacher engages in ongoing professional learning and uses evidence to continually evaluate his/her practice, particularly the effects of his/her choices and actions on others (learners, families, other professionals, and the community), and adapts practice to meet the needs of each learner.
Standard 10: Leadership and Collaboration—The teacher seeks appropriate leadership roles and opportunities to take responsibility for student learning, to collaborate with learners, families, colleagues, other school professionals, and community members to ensure learner growth, and to advance the profession.

SOURCE: CCSSO 2013.

Despite some differences, these two conceptions of the professional knowledge base of K–12 educators align in a number of ways. They treat similarly aspects of teaching practice (planning or reflection, for example); strategies for teaching and for enabling learning; approaches to organizing and managing the spaces in which learning takes place; and how teachers' work with students, parents, administrators, and colleagues inside and outside of classrooms.

Certainly, many elements of these general frameworks will be relevant to the preparation of K–12 teachers of engineering, but these educators also have unique learning needs. Unfortunately, there has been little direct scholarship on the specific professional knowledge base for teachers of engineering. Despite this limitation, researchers have drawn on studies and the experience of practitioners to create guidelines, such as the *Standards for Preparation and Professional Development of Teachers for Engineering* (Farmer et al. 2014; box 5-3), to help support teacher professional learning in this domain. Because they focus on teacher professional learning rather than on teaching as in the previous frameworks, these standards highlight not only what teachers need to know but how they might learn it.

BOX 5-3
Standards for the Preparation and Professional Development for Teachers of Engineering

Standard A: Engineering Content and Practices:
Professional development for teachers of engineering should address the fundamental nature, content, and practices of engineering as defined above. To promote literacy in the category of engineering design, it should:

1. Engage teams of participants in authentic engineering practices and processes (i.e., participating in the engineering design process as initiated by a design challenge statement, through at least one improvement cycle, and involving communication of results);
2. Introduce participants to tools that enable success in engineering; such tools include engineering notebooks, simple tools (e.g., rulers), and more sophisticated technologies (e.g., computer probeware and software, digital multimeters);
3. Introduce participants to strategies that enable success in engineering; key strategies include engaging in teams, asking questions, communication about design, and carefully documenting work;
4. Encourage participants to reflect on multiple experiences with the engineering design process, whether these have occurred within or outside the context of the current professional development opportunity, to reinforce learning about engineering content and practices; and
5. Enable participants to compare design in engineering to design in other fields (e.g., fashion, architecture, art).

To promote literacy in the category of engineering careers, such professional development should:

1. Provide opportunities for participants to learn about engineering fields and professions;
2. Engage participants in comparing engineering with non-engineering content areas (e.g., mathematics, science, social studies, English language arts, the arts, technology education);
3. Engage participants in comparing classroom-based engineering experiences with professional engineering practice; and
4. Provide opportunities for educators to learn about the pre-collegiate and collegiate academic preparation required for engineering careers.

To promote literacy in the category of engineering and society, such professional development should:

1. Provide opportunities for participants to explore the work of engineers and their contributions to society, as well as ways in which some engineered solutions have caused societal challenges.

Standard B: Pedagogical Content Knowledge for Teaching Engineering:
Professional development for teachers of engineering should emphasize engineering pedagogical content knowledge. It should:

1. Engage participants in exploring teaching and learning in engineering and how it is similar to, and different from, teaching and learning in science and/or mathematics;
2. Introduce participants to effective classroom management strategies for enabling learning in engineering;
3. Foster participants' ability to develop design challenges that are appropriate for their student population, teaching environments, and/or local community;
4. Facilitate participants' reflection upon their own teaching practice and encourage participants to seek feedback from others to refine and optimize their engineering teaching practice; and
5. Promote and support participants' engagement with engineering mentors who can, in turn, support participants' teaching of engineering through a variety of approaches (e.g., field experiences, field trips, internships, collaborations, classroom visits).

Standard C: Engineering as a Context for Teaching and Learning*:*
Professional development for teachers of engineering should make clear how engineering design and problem solving offer a context for teaching standards of learning in science, mathematics, language arts, reading, and other subjects. It should:

1. Enable participants to explore research that demonstrates how using engineering design and problem solving as a context for learning improves students' critical thinking skills and academic achievement;
2. Engage participants in engineering design challenges that require horizontal integration with non-engineering content (e.g., mathematics, science, social studies, English language arts, the arts, technology education);
3. Draw attention to the way in which engineering design and problem solving reinforce skills (e.g., 21st century skills such as creativity, communication, critical thinking, and collaboration) and practices (e.g., modeling, data analysis, and presentation) that are relevant to many fields; and
4. Encourage participants to integrate engineering into the existing curriculum.

Standard D: Curriculum and Assessment*:*
Professional development for teachers of engineering should empower teachers to identify appropriate curriculum, instructional materials, and assessment methods. It should:

1. Enable participants to identify engineering curriculum that is developmentally, instructionally, and cognitively appropriate for their students;
2. Engage participants in evaluating the potential of engineering curriculum to address one or more sets of student learning standards (e.g., ITEEA learning standards, Next Generation Science Standards, state standards);
3. Engage participants in evaluating the potential of engineering curriculum to support a particular set of engineering learning objectives;
4. Engage participants in evaluating the adaptability of engineering curriculum to local conditions (e.g., scheduling/timing, emphasis on content/methods, cultural context, similarity to other activities in an existing curriculum);

5. Engage participants in evaluating the available teacher support for a particular engineering curriculum;
6. Engage participants in examining the authenticity and appropriateness of formative and summative assessments embedded in a curriculum; and
7. Demonstrate connections and alignment between engineering curriculum, instruction, learning, and assessment.

Standard E: Alignment to Research, Standards, and Educational Practices:
Professional development for teachers of engineering should be aligned to current educational research and student learning standards. It should:

1. Be developed and refined in collaboration with experts in the fields of engineering, engineering pedagogy, and teacher professional development;
2. Be developed and refined in collaboration with stakeholders (e.g., state education agency personnel, school administrators, teachers);
3. Enable participants to experience the curriculum that they will teach;
4. Model effective engineering teaching practices;
5. Employ differentiated instruction techniques;
6. Be guided by formative assessment;
7. Encourage risk-taking by participants;
8. Be longitudinal; and
9. Evolve through a process of continuous improvement that employs ongoing evaluation, assessment and revision.

SOURCE: Farmer et al. (2014). Reprinted with permission.

In developing the standards, Farmer and colleagues turned to a previous, similar effort in science education, the National Science Education Standards (NSES; NRC 1996). They took the general principles for teacher professional development (PD) described in NSES and incorporated ideas from the emerging consensus on learning goals for K–12 engineering education (e.g., NAE and NRC 2009). They also reviewed relevant research in science education, teacher preparation and development, and adult learning. (Reimers et al. 2015 summarize the research base underlying the standards.) Stakeholders in K–12 and postsecondary education provided input on drafts of the standards. Farmer and Klein-Gardner (2014) then used the final version of the document to create a matrix that providers of PD for K–12 teachers of engineering could use to map their efforts to elements in the standards. Ten providers of K–12 engineering professional development beta-tested the matrix before it was published by the American Society for Engineering Education.

Although the focus of the standards is on providing high-level guidance to teacher education and PD programs, not on the desired competencies of K–12 engineering teachers per se, normative guidance for high-quality programs can suggest the professional knowledge required for high-quality engineering instruction. And while some elements of the standards are consistent with the general guidance in the Danielson and Sykes/Wilson frameworks, they also differ in significant ways, particularly Standard A, which addresses engineering content and practices, and Standard B, which addresses pedagogy.

Because K–12 technology or science teachers may teach engineering (see chapter 4), the committee also reviewed standards for professional learning in those subjects for additional insights into the learning needs of K–12 teachers of engineering. *Advancing Excellence in*

Technological Literacy: Student Assessment, Professional Development, and Program Standards (*AETL*; ITEA 2003) is a companion volume to the *Standards for Technological Literacy: Content for the Study of Technology (STL)* developed by the technology education community (ITEA 2000). As noted in chapter 2, *STL* expects students to understand and be able to apply the engineering design process. Presumably, the same should be true for technology teachers. Although *AETL* does not call out these engineering-specific learning goals for teachers, they are implied in Standard PD-1, which expects teacher education programs to provide prospective teachers with "knowledge, abilities, and understanding consistent with" *STL* (p. 42).

As noted in chapter 4 (box 4-2), new standards for science teacher preparation programs (Morrell et al. 2019) include elements of engineering. For example, Standard 1, on content knowledge, calls on prospective teachers to "connect important disciplinary core ideas, crosscutting concepts, and science and engineering practices for their fields of licensure" (p. 1). Standard 2c, on content pedagogy, specifies that teachers should be able to "Us[e] engineering practices in support of science learning wherein all students design, construct, test and optimize possible solutions to a problem" (p. 1). And Standard 5a, related to impacts on student learning, expects prospective teachers to "implement assessments that show all students have learned and can apply disciplinary knowledge, nature of science, science and engineering practices, and crosscutting concepts in practical, authentic, and real-world situations" (p. 3).

However, the *Standards for the Preparation and Professional Development of Teachers of Engineering* is by far the most detailed and most relevant to the committee's statement of task. With the exception of Goal 4's expectations related to preparation for matriculation in postsecondary engineering programs, the standards provide a reasonable, if aspirational, outline of the knowledge and skills needed by K–12 teachers of engineering. They also address a number of the general concerns in the Danielson and Sykes/Wilson frameworks related to such issues as classroom management, assessment, working with diverse populations, and the need for continuous improvement.

Engineering Content and Practices

We now turn from the general guidance provided by teacher PD standards to more specific ideas about the knowledge base for K–12 teachers of engineering in three critical areas of engineering content and practice: engineering design, STEM integration, and science and mathematics for engineering. This section draws on a limited number of scholarly publications, nearly all of which are descriptive in nature, and sources such as teacher preparation course descriptions and frameworks for teacher certification. As noted in chapter 1, descriptive research may provide a basis for developing additional testable hypotheses about causes, and it may offer some testable insights about potential mechanisms, but it cannot be used to make causal claims.

Engineering Design

It seems logically sound to assert that all engineering teachers should have a foundational level of engineering literacy. A key aspect of such literacy is to understand the engineering design process, which includes both content (the concepts embedded in the process) and practices (carrying out the process itself). Research suggests that practicing the process of engineering design enables K–12 teachers to (1) develop their content knowledge in engineering (Custer and Daugherty 2009; Donna 2012; English et al. 2013; Moore et al. 2014) and (2) increase their comfort and proficiency with the skills and strategies of engineering design (Brophy et al. 2008; Hsu et al. 2011).

A potential pitfall of working toward new models of instruction, especially for those who have little or no experience with a given subject area, is reducing complex instructional tasks in an effort to simplify implementation without attention to the underlying intellectual work in which students need to engage. For instance, teachers who do not have a full grasp of the engineering design process may reduce it to a sequence of steps that students must memorize and follow exactly (McCormick 2004) rather than teaching it as an iterative, collaborative, and creative process as described in chapter 2. One study found that teachers implementing an engineering lesson for the first time focused on the activity's logistics (e.g., specific steps in the design process) rather than the connections to engineering work, science, or mathematics (Diefes-Dux 2014).

It is only once teachers gain a comfort level with the logistics that they begin to consider connections with other subjects and achieve deeper understanding of engineers and engineering. In addition, teachers with little exposure to engineering design may adopt a deficit model of failure, seeing failure as negative and something to be avoided (Lottero-Perdue and Parry 2014). In contrast, those with experience delivering curriculum that treats failure as an opportunity for student growth come to see failure as an important element of instruction (Lottero-Perdue 2015; Lottero-Perdue and Parry 2017).

A multiple case study that examined five engineering PD programs associated with curriculum development projects for high school teachers found that the programs emphasized the process of design rather than disciplinary knowledge needed for engineering work or pedagogical content knowledge (Daugherty and Custer 2012). Professional learning experiences that delved more deeply into the engineering process—for example, by exploring the roles of analysis, systems, and modeling—helped educators not only develop deeper understanding of these concepts and practices but also integrate engineering activities in their classrooms to promote student science learning (Custer et al. 2014).

For purposes of assessment, it may be important for K–12 teachers of engineering to understand and have experience with the many forms that student design solutions can take (Brophy et al. 2008). Assessing student design activities differs in many ways from the grading of activities with clear right and wrong answers (e.g., addition and subtraction, naming the parts of a cell), and this suggests a need for professional learning experiences that explicitly target assessment (Hynes et al. 2014). Studies have called for the development of frameworks to support teachers as they create and use their own tools to assess student learning in engineering design (Diefes-Dux et al. 2012; Hjalmarson and Diefes-Dux 2008).

STEM Integration

The different goals for K–12 engineering education suggest that many teachers of engineering will need to master concepts and practices that go beyond engineering design. Chapter 3 ("The Goal of Improving Mathematics and Science Achievement through Integrated STEM Learning") discusses the potential benefits to students of experiencing STEM education in a more integrated way. For this to occur, teachers must be able to create learning opportunities that leverage connections between and among STEM concepts and practices. This capability would be important not only for technology and engineering educators, who need to support students' use of science and mathematics ideas to address engineering challenges, but also for science and mathematics teachers tasked with integrating engineering concepts and practices into their instruction, as called for in the Next Generation Science Standards (NGSS Lead States 2013).

One potential benefit of STEM integration that involves engineering is that students may achieve deeper learning of science and mathematics concepts when exploring them in the context of engineering design. In addition, learning science and mathematics through relevant, real-world design challenges may boost student interest and motivation to learn. The committee again acknowledges that, as noted in chapter 3, the evidence for engineering leading to learning or achievement in science and mathematics is mixed (NAE and NRC 2014, pp. 56–60), the number of high-quality studies in this area is limited (e.g., Fortus et al. 2004; Klein and Sherwood 2005; Kolodner et al. 2003), and there is similarly limited evidence of the potential of STEM integration to affect student engagement. However, some major education reform efforts, such as the Next Generation Science Standards (NGSS Lead States 2013), are moving in the direction of integration and, as noted in the framework for NGSS (NRC 2012, p. 12):

> [E]ngineering and technology provide a context in which students can test their own developing scientific knowledge and apply it to practical problems; doing so enhances their understanding of science—and, for many, their interest in science—as they recognize the interplay among science, engineering, and technology. We are convinced that engagement in the practices of engineering design is as much a part of learning science as engagement in the practices of science.

Science and Mathematics for Engineering

Student learning goals in engineering, technology, and science and teacher preparation standards in these subjects all note the importance of being able to use appropriate concepts and practices from science and mathematics to inform engineering problem solving. Despite interest among practitioners and policymakers in the idea of K–12 STEM integration, however, researchers have made few attempts to identify the specific ideas and practices from science and mathematics that students or teachers need in order to support their engineering learning or teaching.

Although there is limited empirical evidence in this area, there are at least three ways of thinking about the science and mathematics knowledge that K–12 teachers of engineering require. Teachers might be expected to have a baseline of knowledge of key concepts/practices across several subdisciplines in mathematics (i.e., in keeping with the Common Core State Standards [NGA Center for Best Practices, Council of Chief State School Officers 2010]) and science (i.e., in keeping with NGSS [NGSS Lead States 2013]), regardless of when it is applied. They might need to know concepts and/or practices that are directly relevant to a particular design problem or context. Or they might need both a general baseline of knowledge and specific knowledge relevant to a particular design activity.

Logically, the breadth and depth of science and mathematics knowledge needed by K–12 teachers of engineering will vary according to grade, the specific curriculum, and the goals of instruction. Many elementary teachers already teach basic science and mathematics, so the question for this group may be how and under what circumstances this baseline of knowledge might be supplemented. For example, the Engineering is Elementary curriculum includes an engineering challenge based on construction of a solar oven: 3rd and 4th grade students need to learn science ideas related to heat transfer in order to complete the project (Cunningham 2018, pp. 34–35), and use mathematical skills to calculate rates of change. In a curriculum developed at the Hofstra Center for STEM Research, middle school students tasked with designing a bedroom[1] complete a set of "knowledge and skill builders," short, focused activities to help them identify the variables that affect the performance of the design (Burghardt and Krowles 2006). The students learned mathematical ideas related to geometric shapes, factoring, percentage, and scale.

As teachers become more specialized at the middle school and, especially, high school levels, those who teach engineering will likely need deeper understanding about a greater number of science and mathematics ideas, as well as knowledge of how to help students apply them in service to engineering. Research finds some technology teacher preparation programs include few if any higher-level mathematics and science courses (Litowitz 2014), suggesting a possible weakness in this source of K–12 teachers of engineering.

Beyond these kinds of context-specific examples, there are very few places to turn for guidance on what science and mathematics concepts are most relevant to K–12 engineering education. One exception is a taxonomic structure for high school engineering (Huffman et al. 2018) that may in part address the needs of teachers of more advanced engineering classes (Goal 4 from chapter 3). To create the taxonomy, the researchers used a three-round Delphi study to identify initial content and expert focus groups to provide more detailed concept development. The taxonomy spells out core concepts and subconcepts in science and mathematics that students exploring different subdisciplines of engineering should understand (table 5-2). For example, core concepts in many disciplines of engineering are statics, dynamics, mechanics of materials, and electrical power, each of which have several subconcepts. Some of these require mathematics understanding (e.g., stress-strain analysis, force acceleration), while others implicate science understanding (e.g., materials characteristics, properties, and composition, magnetism).

TABLE 5-2 Abbreviated sample of core concepts and subconcepts of engineering for secondary school students.

Core Concept of Engineering	Subconcepts
Statics	Resultants of force systems
	Equivalent force systems
	Equilibrium of rigid bodies
Dynamics	Kinematics (e.g., particles and rigid bodies)
	Mass moments of inertia
	Force acceleration (e.g., particles and rigid bodies)
Mechanics of Materials	Stress types and transformations
	Material characteristics, properties, and composition (e.g., heat treating)
	stress-strain analysis
Electrical Power	Motors and generators
	Transmission and distribution
	Magnetism

SOURCE: Huffman et al. (2018). Reprinted with permission.

[1] https://www.hofstra.edu/academics/colleges/seas/ctl/itea/itea_activity_bedroomdesign.html

One limitation of this work for the committee's purposes is that the taxonomy targets student learning, not teacher learning. However, it is reasonable to expect that teachers of engineering, especially those teaching more advanced classes, would need at least the same level of subject-matter knowledge in science and mathematics as the students they teach. Given the broader literature on teacher professional knowledge, it is also likely that that minimal knowledge would be inadequate and teachers would probably need more extensive content knowledge, as well as relevant pedagogical content knowledge (discussed below). In any case, this is one of the few examples the committee could find that attempts to describe the landscape of mathematics and science concepts relevant for higher-level work in K–12 engineering.

Another possible approach to determining the requisite knowledge in science and mathematics needed by K–12 teachers of engineering is to examine the content frameworks for state teacher certification tests in this area. An analysis of all such frameworks was beyond the committee's scope of work, but examination of a small number of such documents shows considerable variation in their content. One detailed certification framework for prospective engineering teachers is the Texas TExES Mathematics/Physical Science/Engineering 6–12 teacher examination,[2] which covers 12 domains, two of which (Engineering Method and Engineering Profession) specifically address engineering (table 5-3). (Questions based on content from these two domains account for 30 percent of credit on the exam.)

TABLE 5-3 Engineering-Related Domains and Standards in Texas's Certification Exam for Grade 6–12 Teachers of Mathematics/Physical Science/Engineering.

Permission Pending

SOURCE: Texas Education Agency (2018).

[2] Information about the exam is available at https://www.tx.nesinc.coTm/TestView.aspx?f=HTML_FRAG/TX274_TestPage.html, and a preparatory manual is available here: https://www.tx.nesinc.com/Content/Docs/274PrepManual.pdf.

Each domain has standards with associated competencies that broadly define the knowledge and skills that beginning teachers should possess and include details about what specific knowledge and skill the certification exam will cover. Most relevant to this study is Competency 044,[3] which spells out the knowledge of engineering fundamentals that the "beginning teacher" should have:

A. Applies principles related to statics (e.g., moment, stress, strain) to analyze systems and solve problems.
B. Applies principles of dynamics (e.g., force, acceleration, moment of inertia) to model and solve problems.
C. Understands terminology (e.g., analog, digital) and concepts related to electric circuits (e.g., circuit analysis, digital logic circuits).
D. Applies principles of fluid mechanics (e.g., Pascal's law, Bernoulli's law) to solve problems in fluid flow.
E. Understands the applications of thermodynamics (e.g., heat transfer, energy conversions, efficiency) to engineering systems.
F. Understands terminology and concepts related to control systems (e.g., input, output, feedback).
G. Understands and applies the concepts of sketching and skills associated with computer-aided drafting and design.
H. Applies mathematical principles of pneumatic pressure and flow to model and solve problems.
I. Applies mathematical principles of manufacturing processes in lathe operations and computer numerical control mill programming to model and solve problems.
J. Applies mathematical principles of material engineering to model and solve problems.
K. Applies mathematical principles for mechanical drives to model and solve problems.
L. Applies mathematical principles of quality assurance (e.g., using precision measurement tools) to model and solve problems.
M. Applies mathematical principles of robotics and computer programming of robotic mechanisms to model and solve problems.

The framework does not explain the process used to select the specific concepts. As is the case more generally, this list is likely the result of a normative analysis of the relevant content to be taught, not a list of aspects of teacher knowledge that have been found to empirically correlate with high-quality engineering teaching or student learning. To a considerable degree, this list of science and mathematics concepts accords with the major course-content buckets of traditional postsecondary engineering programs: statics, dynamics, fluids, thermodynamics, and circuits. This is not surprising, since many of the reference documents cited in the framework appear to be course textbooks. Whether this is the most appropriate selection of such ideas for prospective secondary teachers of engineering, the committee cannot say, given the lack of empirical evidence. That said, the list offers a hypothesis about requisite teacher knowledge that could be tested in future research.

Pedagogical Content Knowledge for K–12 Engineering

[3] https://www.tx.nesinc.com/content/docs/274PrepManual.pdf, page 36.

In addition to content knowledge of the subject they are teaching and general understanding of pedagogical methods, teachers need pedagogical content knowledge (PCK), which involves subject-specific aspects of student learning, curriculum, and the most effective ways to teach about particular subject-matter ideas. PCK has been described as “the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction” (Shulman 1987, p. 8). The concept has gained considerable traction in research on K–12 science and mathematics teaching and teacher development, as well as evolved over time as research and practice point to strengths and weaknesses in both the concept and its operationalization in practice and research (e.g., Gess-Newsome and Carlson 2013).

A three-part definition of PCK based on both logical analysis and empirical assessments of teacher knowledge (Ball et al. 2008) can be adapted to engineering to yield three PCK domains:

- knowledge of how students think about, experience, and understand engineering;
- knowledge of engineering curricula; and
- knowledge of instructional strategies that are particularly powerful in teaching engineering.

All three domains are important, and we now consider research that touches on one or more of them.

Sun and Strobel (2014) conducted observations and interviews with elementary teachers who participated in a weeklong PD summer institute using the Engineering is Elementary (EiE) curriculum. The researchers found that teachers uncovered numerous student misconceptions about engineering and technology, a finding well documented by other researchers (e.g., Cunningham 2008) and very important to the development of PCK. Participating teachers also learned that many students lacked teamwork abilities, which, although important in many school settings, is a particularly important element of the engineering design process. They also confronted problems with assessing their students’ engineering work and learning. The teachers tried several classroom techniques to manage both teaching engineering and assessing student outcomes, and in the course of trying different strategies developed engineering PCK. Sun and Strobel suggest that teachers who learn engineering content in professional learning situations need the experience of teaching in real-world settings to enable their PCK development. Further research would inform the development of the specifics of what engineering PCK might include.

Another potential resource for conceptualizing PCK is Crismond and Adams’ (2012) “informed design teaching and learning matrix” (p. 741). The matrix (table 5-4) is a use-inspired framework (Turns et al. 2006) that aims to describe the PCK needed to teach with design tasks. It was developed using a scholarship-of-integration approach, a synthesis of literature on design-based learning and performances across a range of contexts. The authors describe eight design strategies (table 5-4, column 1) and associated behaviors of beginning and informed designers (columns 2 and 3), and link these descriptions to both learning objectives and teaching behaviors (last two columns). The few developmental research studies in engineering design did not enable the authors to describe the performances at different grade levels, which would have enhanced the matrix’s utility. The matrix has not been tested empirically as a tool for teacher professional development.

TABLE 5-4 The Informed Design Teaching and Learning Matrix

Design Strategies	**Beginning vs. Informed Designers**		**Learning goals where students…**	**Teaching strategies where students…**
	Beginning designers…	Informed designers…		
Understand the Challenge	**Pattern A. Problem Solving vs. Problem Framing**		Define criteria and constraints of challenge. Delay decisions until critical elements of challenge are grasped.	State criteria and constraints from design brief in one's own words. Describe how preferred design solution should function and behave. Reframe understanding of problem based on investigating solutions.
	Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve.	Delay making design decisions in order to explore, comprehend and frame the problem better.		
Build Knowledge	**Pattern B. Skipping vs. Doing Research**		Enhance background knowledge, and build understandings of users, mechanisms and systems.	Do info searches and read case studies. Write product history report. Do studies and research on users. Reverse engineer existing products. Conduct product dissections.
	Skip doing research and instead pose or build solutions immediately.	Do investigations and research to learn about the problem, how the system works, relevant cases, and prior solutions.		
Generate Ideas	**Pattern C. Idea Scarcity vs. Idea Fluency**		Generate range of design ideas to avoid fixation. Know guidelines and reasons for various divergent thinking approaches.	Do brainstorming and related techniques to achieve idea fluency. Relax real-world constraints or alter original task to see it in new ways. Do generative database searches.
	Work with few or just one idea, which they can get fixated or stuck on, and may not want to change or discard.	Practice idea fluency in order to work with lots of ideas by doing divergent thinking, brainstorming, etc.		
Represent Ideas	**Pattern D. Surface vs. Deep Drawing & Modeling**		Explore and investigate different design ideas via sketching, modeling solutions, and making simple prototypes.	"Mess about" with given models. Use words, gestures, artifacts to scaffold visualizing solutions. Do rapid prototyping using simple materials or various drawing tools. Conduct structured review of ideas.
	Propose superficial ideas that do not support deep inquiry of a system, and that would not work if built.	Use multiple representations to explore and investigate design ideas and support deeper inquiry into how system works.		
Weigh Options and	**Pattern E. Ignore vs. Balance Benefits & Tradeoffs**		Consider both the benefits and tradeoffs	Give explanations for design choices. Describe

Make Decisions	Make design decisions without weighing all options, or attend only to pros of favored ideas, and cons of lesser approaches.	Use words and graphics to display and weigh both benefits and tradeoffs of all ideas before picking a design.	of all ideas before making design decisions.	and portray pros and cons for all design options under consideration. Articulate design values and advice like KISS (Keep It Super Simple) and human-centered design.
Conduct Experiments	**Pattern F. Confounded vs. Valid Tests & Experiments**		Run valid "fair test" experiments to learn how proto- types behave and to optimize their performance.	Create design advice for others and generalizations based on valid tests. Do investigate-and-redesign and product comparisons tasks. Do tests to optimize performance.
	Do few or no tests on prototypes, or run confounded tests by changing multiple variables in a single experiment.	Conduct valid experiments to learn about materials, key design variables and the system work.		
Troubleshoot	**Pattern G. Unfocused vs. Diagnostic Troubleshooting**		Diagnose and troubleshoot ideas or prototypes based on simulations or tests.	Follow troubleshooting steps: observe, name, explain, and remedy. Do troubleshooting stations/videos. Do modeling or cognitive training in troubleshooting.
	Use an unfocused, nonanalytical way to view prototypes during testing and troubleshooting of ideas.	Focus attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them.		
Revise and Iterate	**Pattern H. Haphazard or Linear vs. Managed & Iterative Designing**		Manage project resources and time well. Use iteration to improve ideas based on feedback. Employ design strategies repeatedly in any order as needed.	Use design storyboards to record progression of their work. Give instruction and scaffolding for project management & design steps. Encourage taking risks, learning while iterating, and reflecting on how the design problem is framed.
	Design in haphazard ways where little learning gets done, or do design steps once in linear order.	Do design in a managed way, where ideas are improved iteratively via feedback, and strategies are used multiple times as needed, in any order.		
Reflect on Process	**Pattern I. Tacit vs. Reflective Design Thinking**		Periodically reflect while designing and keep tabs on strategies used. Review to check how well solutions met goals.	Keep design diaries and portfolios. Compare/contrast design cases of approaches used by different groups. Do computer-supported structured reflections about design work.
	Do tacit designing with little self-monitoring while working or reflecting on the process and product when done.	Practice reflective thinking by keeping tabs on design strategies and thinking while working and after finished.		

SOURCE: Crismond and Adams (2012). Adapted with permission.

Crismond and colleagues (Crismond 2013; Crismond and Adams 2012; Crismond et al. 2013; Crismond and Peterie 2017) have described activities that teachers can do to increase their design PCK and help their students become informed designers. One example is the area of troubleshooting. Teachers are likely already familiar and experienced with troubleshooting their own technology when it does not work properly (e.g., shutting down programs to see if the phone or computer will improve its performance), but troubleshooting for design involves more specialized knowledge and behaviors. Teachers can develop this PCK during prototype testing by following a procedure of observing the behavior of the prototype, diagnosing and describing unexpected performance, hypothesizing explanations for that behavior, and proposing redesign solutions (Crismond and Peterie 2017). Crismond and Peterie describe a Troubleshooting Portfolio that Peterie, a high school physics and engineering teacher, has used to both help him improve his engineering PCK and help his students develop their own skills.

Using the informed design teaching and learning matrix, the *Standards for the Preparation and Professional Development of Teachers of Engineering* (Farmer et al. 2014), and other resources related to the teaching and learning of engineering, Lomask and colleagues (2018) developed design teaching standards within the dimensions of informed design practices, engineering themes, and classroom instructional practices. The standards, which underwent validity but not reliability testing, describe what teachers using engineering tasks need to know and do in the classroom to provide their students opportunities to learn. For example, in order to address the dimension of informed design practices, teachers should allow students to frame the challenge, do research, generate alternatives, make decisions, prototype, test, iterate on and improve the design, and communicate and reflect on the process. Engineering themes encompass design, models, systems, resources, and human values and the impact on users. Classroom instructional practices incorporate STEM concepts, appropriate lesson plans, academic learning (e.g., literacy, information technology), practical learning (e.g., safe use of tools), team work, and assessments (Lomask et al. 2018).

Hynes (2012) also examined how teachers come to understand and teach students about the engineering design process. The study involved six middle school science, mathematics, and computer science teachers who had participated in a 15-hour PD workshop designed to support use of a specific engineering curriculum, the LEGO robotics toolset, and ROBOLAB programming language. The project took place in Massachusetts, which has articulated an eight-step engineering design process for K–12 education (Massachusetts Department of Education 2006), and Hynes rated teachers on their explanations of those eight steps using a locally developed measure. Teachers' abilities to explain the steps varied from low to high across the eight steps, indicating that teachers were at different stages of understanding the design process. The analyses also revealed that teachers were beginning to develop relevant pedagogical content knowledge, including real-world examples or familiar analogies that they could use to help students understand design concepts like "prototype."

As a small-scale study, the Hynes research is useful in helping us theorize about teachers' learning needs: even in a well-developed program with a great deal of support, middle school teachers charged with integrating engineering into their curriculum needed more than a summer PD opportunity and a well-developed curriculum. They needed time to experiment, to reflect, and to build a classroom-based knowledge of how to adapt the lessons for their students. They also did not proceed in lock-step fashion but rather were more successful implementing some of the materials than others. It seems prudent to presume that all middle and high school teachers, even those who have studied engineering extensively, will face challenges in building the knowledge and skills necessary to integrate engineering in their curricula. This observation, if it holds true for a broader set of teachers, has implications for the infrastructure necessary to support teachers' learning over time, an issue that we address in chapter 6.

The results of these studies resonate with the broader research literature on professional development and teacher education. That literature suggests that teachers benefit by reflecting on both the professional learning experience itself and how to use new information in teaching (e.g., Penuel et al. 2007; Rogers et al. 2007; Thompson and Zeuli 1999). This includes examining student work, engaging in capstone projects that enhance reflection, and having multiple opportunities to experiment in classrooms and reflect on the experience (e,g, Boyd et al. 2009, 2012; Cohen and Hill 2001; Darling-Hammond et al. 2017; Heller et al. 2012; Little 2003; Roth et al. 2011).

Teachers may not always have adequate time to develop PCK, however. This was the case in the five high school engineering PD programs documented by Daugherty and Custer (2012). The researchers suggest that this may have been because the programs had started as curriculum development projects, and program leaders viewed professional development as a way to introduce teachers to the curricula. But curricula alone do not ensure that instruction is transformed. Although the educators followed the same hands-on activities they would then use with students, thus engaging in active learning, the low level of reflection and discussion, coupled with limited time devoted to ongoing practice using the materials in their classrooms, did not allow them to think about how best to implement what they were learning in the classroom, and thus they missed an opportunity to build PCK.

Knowledge of Diverse Students

An important aspect of PCK is understanding and leveraging student perspectives and needs across contexts and grade levels. This is particularly relevant given the diversity of backgrounds and experiences US K–12 students bring to the classroom. This diversity argues for the use of inclusive pedagogies (box 5-4) that can make education more culturally, linguistically, and socially relevant.

BOX 5-4

Permission Pending

Among their potential benefits, inclusive teaching methods may help reduce longstanding achievement gaps between white and African American and Hispanic students, and between low-income students and students of higher income, which have been documented in K–12 engineering (box 5-5). More broadly, inclusion approaches hold the promise of potentially interesting students from all backgrounds in the study of engineering, a field with a poor track record of attracting and retaining women and people of color (table 4-4).

At their core, such approaches are "based on the idea that underrepresented students' cultural and linguistic practices are assets rather than deficits or barriers to the learning process" (Wilson-Lopez 2016, p. 1). For example, Jordan and colleagues (2017), working to create an engineering curriculum for Navajo Nation middle school students, note the "similarities between the Navajo way of life, which is a holistic cycle of thinking, planning, living, and assuring/testing" and the engineering design process. In a specific instance of curriculum design for greater inclusivity, researchers (Kern et al. 2015) at the University of Idaho developed middle school curriculum in which students designed and tested fish weirs, a traditional Native American technology for catching fish whose basic principles are still in use today. As an extension activity, students worked with community members to build a full-scale, functional weir in a local stream. Wilson-Lopez and colleagues (2016) explored engineering-related funds of knowledge among a group of 25 Latino/a middle and high school students as they designed and implemented engineering projects in their communities. According to the researchers, the students gained significant insights into problem definition from aspects of their daily lives, such as work experiences, familiarity with injury-related health issues of family members, and their perspectives as "transnationals" in regular contact with relatives in other countries.

BOX 5-5
Achievement Gaps in the National Assessment of Technology and Engineering Literacy (TEL)

The share of eighth-grade students performing at or above the proficient level in TEL, a national assessment given to large samples of 8th graders, rose from 43 in 2014 to 47 percent in 2018. According to National Assessment Governing Board, these students demonstrate solid academic performance and competency in challenging subject matter.

The percentages of Black students performing at or above proficient was just 18 percent in the 2014 administration; it rose to 24 percent in 2018. Among Hispanic students, 28 and 31 percent tested at this level in 2014 and 2018, respectively. By comparison, 56 percent of both White and Asian students attained this level of achievement in 2014, and in 2018 their scores rose to 59 and 66 percent, respectively.

Reflecting the influence of household wealth on academic performance, 25 and 30 percent of students eligible for school lunch programs, an indicator of low income, achieved at or above proficient on TELS in 2014 and 2018, respectively, compared with 60 and 61 percent of students ineligible for assistance in those two years, respectively.

SOURCE: Calculations done using the NAEP Data Explorer, https://www.nationsreportcard.gov/ndecore/landing, August 5, 2019.

As part of the effort to adopt more inclusive pedagogies, teachers may also need to recognize and overcome some of their own views about who "belongs" in engineering. Research using the

Engineering Beliefs and Expectation Instruments for Teachers (EEBEI- T) provides insights into how teachers' think about which students should enroll in engineering classes and which would be most likely to succeed in an engineering career. EEBEI-T asks teachers to respond to survey questions and evaluate a series of fictional student vignettes. EEBEI-T was validated in a study involving 144 high school STEM teachers in an urban city in the Midwestern United States (Nathan et al. 2009). In answering the survey questions, study participants indicated academic performance in mathematics, science, and technology was the most important factor in judging a student's suitability for future study or a career in engineering. Family background was deemed somewhat important, and socioeconomic status was not a factor. However, in the vignettes, academic performance (engineering course grade and GPA) was unequally applied. It was a major factor for fictional students with a privileged background but much less important for students with low socioeconomic status (SES), suggesting that, despite explicitly ruling out SES as a factor in their decision making in their survey responses, the teachers implicitly used SES status in judging the vignettes. Nathan et al. 2011 documented similar findings in research involving teachers participating in professional development associated with Project Lead The Way.

TEACHER LEARNING OPPORTUNITIES

We now turn to the second question of this chapter: "What *learning opportunities* will teachers need in order to teach engineering?" Like research on the professional learning needs of engineering teachers, the research base related to professional learning opportunities for K–12 engineering teachers is limited. This is both because there are very few teacher education programs in engineering (see chapter 4, "Programs for Prospective Teachers") and because the number of education researchers working in this domain is quite small. Thankfully, there is a fair amount known from research about effective approaches to teacher preparation more generally, including in science and mathematics. Thus, we begin by examining relevant research, best practices, and standards that apply across multiple fields and then turn to the literature on engineering specifically.

In keeping with contemporary models of teacher professional learning, we conceptualize teacher learning over the arc of an educator's career, starting with quality preparation, followed by quality early-career support, and extending to quality professional development (figure 5-1).

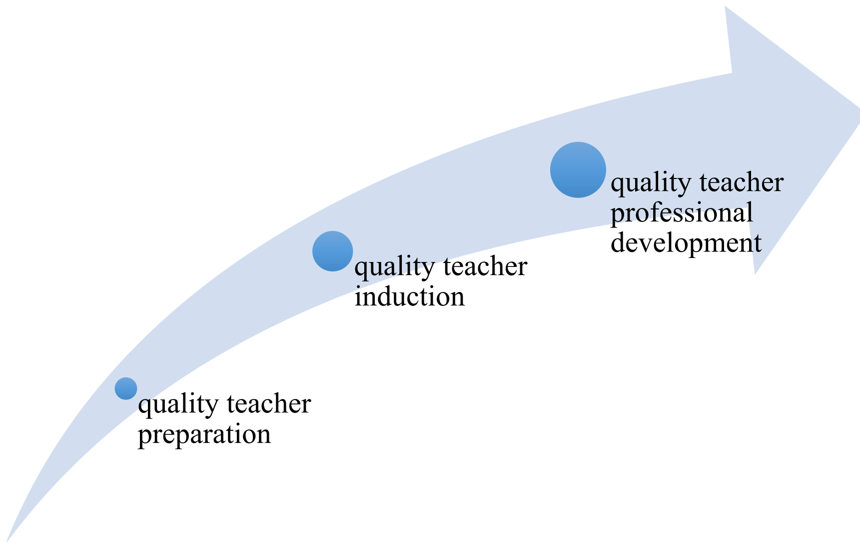

FIGURE 5-1 The Arc of Teacher Professional Learning.
SOURCE: Wilson (2011). Used with permission.

Quality Teacher Preparation

US teacher preparation has been the target of much discussion, debate, and experimentation. The committee's goal is to understand the characteristics of teacher preparation programs associated with producing "well-launched" beginners. A reasonable starting point is the Council for the Accreditation of Educator Preparation (CAEP) standards (box 5-6), which represent a synthesis of evidence (e.g., Cochran-Smith and Zeichner 2005; Darling-Hammond and Bransford 2005; NRC 2010) about effective teacher preparation and serve as high-level guidance to programs engaged in this work.

BOX 5-6

Permission Pending

All five CAEP standards are important. However, given the nascent state of US K–12 engineering educator preparation, we focus on Standards 1 and 2, which relate most directly to development of educator knowledge and skills. A great deal of research has investigated the causal relationship between teacher subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge. Across grade levels and subject areas, it has been difficult to find evidence that teachers with specific levels of content knowledge, PCK, or pedagogical knowledge have students with higher achievement. Problems with accurate measures of teacher content and pedagogical knowledge have plagued the field, and questions remain about whether there are ceiling effects for the amount of content knowledge teachers need.

Nonetheless, many studies have demonstrated associations between teachers' qualifications in their content domains and student achievement. For example, teacher preparation in specific subjects (e.g., earning a mathematics degree before teaching mathematics) correlates positively with student scores in that subject on the National Assessment of Educational Progress (Ingersoll et al. 2014). Similarly, there is general agreement that clinical partnerships between K–12 and postsecondary institutions and high-quality student-teaching experiences are essential to learning to teach. To be effective, these experiences require highly skilled mentors who have learned to support new teachers and who have sufficient time to observe and work with them, as well as systems for providing feedback on the types of instruction that research suggests can increase student learning and engagement (Clift and Brady 2005; Grossman 2010).

Preparation of Teachers of Engineering

The opportunity to take engineering or engineering-related coursework would seem to be an important element of any program preparing K–12 teachers of engineering. Yet the committee could find no research that explicitly explored the relationship between such course taking and effective teaching of engineering at the K–12 level. Fantz and colleagues (2011) found that newly minted teachers from a program that conferred both an undergraduate engineering degree and a technology education teacher license included more engineering concepts in lesson and assignment planning than current technology teachers who had not studied engineering. But this finding, though encouraging, does not tie teacher preparation to student performance in the way Ingersoll and colleagues (2014) do nor shed light on the impacts of one or multiple engineering courses, rather than an engineering degree, on teacher preparation or effectiveness.

We know from Rogers (2012) and Litowitz (2014) that most technology teacher education programs provide very little in the way of engineering content or higher-level mathematics, and the situation in science is similar. Banilower and colleagues (2018) found that just 13 percent of high school science teachers, 10 percent of middle school science teachers, and 3 percent of elementary school teachers had taken at least one engineering course during their undergraduate education. And only 9 percent of middle school and 18 percent of high school math teachers had taken an engineering course. Given these statistics, it is not surprising that prospective teachers of engineering may view the subject as a trial-and-error activity rather than a clearly defined design process (Culver 2012).

However, the literature does describe several programs that allow prospective elementary teachers to learn about engineering, including a single course that is required for all majors (e.g., a problem-based engineering course, as described in Brady et al. 2016); a team-taught course that brings together education and engineering students for a design experience (e.g., Littell and Harman 2017); and a concentration of several engineering-related courses that the student chooses from among other elective topics (Rose et al. 2017). Other institutions offer a certificate program, a minor, a bachelor's degree program, or a combined undergraduate and master's program (O'Brien et al. 2014; Rose et al. 2017). One institution implemented a collaborative project for elementary education majors in a science methods course and biomedical engineering students. The students worked on teams to design and provide afterschool science club, which provided the prospective teachers with both content and perspectives on engineering (Keshwani and Adams 2016; Melander and Adams 2015). As described in chapter 4, the College of New Jersey's Technology Education and Integrative STEM Education K–5 major includes 60 credits of STEM courses, including a required specialization in engineering/technology, mathematics, biology, chemistry, or physics. St. Catherine's University expects all elementary education majors to earn a 3-course (engineering, chemistry, biology) STEM certificate and also offers a STEM minor, and the University of St. Thomas has an engineering education minor for prospective K–8 teachers (O'Brien et al. 2014).

Another model for building capacity for K–12 teachers of engineering involves collaboration between education and engineering departments and faculty during prospective teachers' undergraduate programs. North Carolina State University's bachelor of science in elementary education includes a required course in engineering design methods taught by engineering faculty. Prospective teachers learn to integrate engineering in their elementary teaching activities, specifically connecting to math and science instruction, and graduate with positive attitudes about engineering (DiFrancesca et al. 2014). Hofstra University offers a K–5 STEM education major with four engineering-related courses taught by an engineering professor (O'Brien et al. 2014). The University of St. Thomas offers a course jointly taught between engineering and education faculty that is a required capstone course for both the undergraduate engineering education minor and a graduate certificate in engineering education. The course objectives include demonstrating engineering knowledge and designing an activity that integrates engineering in the topic they teach (Besser and Monson 2014). The University of South Florida offers a capstone course in Contemporary STEM Issues for mathematics and science prospective middle school teachers. The course is taught by a faculty member from engineering with help from faculty from education, engineering graduate students, and individuals working in a local public school district (Thomas et al. 2019). And at Iowa State University, engineering and education faculty offer a Toying with Technology literacy course for elementary and secondary education majors (Genalo et al. 2001). All of these options might serve as important sites for investigating the potential effects of such coursework on prospective teachers' knowledge and effectiveness.

At least one teacher education program, at the University of Maryland Baltimore County, has taken steps to address the lack of diversity in the K–12 STEM teacher workforce. The Sherman STEM Teacher Scholars Program provides a host of supports for prospective STEM teachers who will work in urban and high-needs schools, including a summer bridge program that prepares students for the program; advising, coaching, and mentoring on professional, academic, and personal topics; and fellowships or summer internships in diverse academic settings under the guidance of teacher-mentors (Hrabowski and Sanders 2015). About 40 percent of graduates from the program have been students of color, but is it not clear how many earned degrees in engineering versus other STEM subjects.

One NSF-funded program, the Robert Noyce Teacher Scholarship Program[4] aims to encourage STEM majors to become K–12 teachers, including teachers of engineering. Because Noyce scholarship graduates are required to teach in school districts defined as high need (i.e., with high turnover rates for teachers, where many teachers teach outside their content area,

[4] https://www.nsfnoyce.org/

and/or that serve a high proportion of children from families living below the poverty line[5]), this program has the potential to improve both the preparation and diversity of K–12 teachers of engineering. Some Noyce scholar programs have included partnerships between engineering and education schools (e.g., Villa and Golding 2014) or provided internships with current teachers for engineering and other STEM majors (e.g., Kennedy et al. 2017; Yousuf et al. 2016).

Quality Teacher Induction

Like many professions, teaching is complex work that requires learning over time to master, and teachers acquire a great deal of the necessary knowledge and skill on the job (e.g., Feiman-Nemser 2001; Gold 1999). Ingersoll and colleagues (2014) found that mathematics and science teachers are more likely to leave teaching after their first year than teachers of other subjects; and across all school subjects, teachers with less pedagogical training and practice teaching were more likely to leave teaching after their first year. In recognition of this, many schools and districts provide some type of formal early-career support, often referred to as "induction." Induction can take many forms: the assignment of coaches or mentors, orientation sessions, reduced workloads, workshops on particular topics, and meeting times to enable teacher collaboration. Banilower and colleagues (2018) found that over two-thirds of schools across all grades surveyed have formal teacher induction programs, most lasting two or fewer years.

Despite the interest in early career support programs, there is a very small research literature documenting the content and character of effective teacher induction. In a systematic review of the literature, Ingersoll and Strong (2011) located 500 research papers that they whittled down to 15 studies with sufficiently rigorous empirical evidence. The preponderance of evidence from these studies indicated that support and assistance for beginning teachers can have positive effects on their commitment, retention, and instructional practices. There was modest evidence that students of teachers who participated in early-career support programs demonstrated higher gains on academic achievement tests.

Ingersoll and Strong also found, however, that the strength of the relationship between an induction program and positive effects varied depending on the program's intensity and robustness. For example, teachers in programs with supports such as mentors in the same content area, common planning time with other teachers in their content area, and regularly scheduled times to collaboratively plan with colleagues were more likely to stay in teaching than those without such supports (Smith and Ingersoll 2004; Strong 2009). Similarly, Rockoff (2008) found that new teachers who worked with mentors based in their school had lower attrition rates than those with mentors from a different school, and teachers who received more hours of mentoring had higher student achievement scores than those with fewer mentoring hours.

Glazerman and colleagues (2010) conducted a large-scale study of the impact of comprehensive teacher induction relative to typical early-career support. The research involved randomized experiments in a set of districts that were not already implementing comprehensive induction. Schools were assigned either to (1) a treatment group whose beginning teachers were offered comprehensive teacher induction or (2) a control group whose beginning teachers received the district's usual induction services. The researchers found no significant effects of comprehensive teacher induction on teacher retention or teachers' instructional practices. In addition, they documented no significant effects on student achievement in years one and two. In

[5] https://www.law.cornell.edu/uscode/text/20/1021

year three, in districts and grades in which students' test scores from the current and prior year were available, students of treatment teachers outperformed students of the control teachers.

Clearly, research on comprehensive induction programs is inconclusive. Nonetheless, comprehensive induction programs typically include the following components:

- formal or informal orientation that reviews school and district policies and procedures;
- mentoring that includes regular observations and formative feedback with supports; and
- ongoing PD opportunities that may include study groups, professional learning communities, coteaching, collaborative planning, and/or workshops.

Induction for Teachers of Engineering

The committee found no research on early-career support programs for engineering teachers. This is likely due to the scarcity of teacher preparation programs that graduate teachers equipped to teach engineering and the limited research in the domain of engineering teacher development. A summary of a convocation on the roles of teachers in policymaking for K–12 engineering education included the suggestion that teacher leaders in engineering could design mentoring programs for beginning teachers of engineering (NASEM 2017). This idea is consistent with studies, cited above, showing the value of mentors in teacher induction.

The committee found no research on how content knowledge plays out in the development of an early career engineering teacher. Research in other fields suggests that early career teachers' content and pedagogical content evolves significantly over time (e.g., Adams and Luft 2018; Davis et al. 2006; Nixon et al. 2017).

Quality Professional Development

Teachers need opportunities to acquire new knowledge, adapt to shifting policies, and hone their craft, even after their entry into the profession. In the past 30 years there have been considerable investments in developing and conducting research on effective professional development. It was beyond the scope of the committee to synthesize all of that research and best practice, so as elsewhere we relied on several syntheses of relevant literature. For example, a National Academies report on science teacher learning (NASEM 2015) discussed a "consensus model of effective professional development" with the following characteristics:

- active participation of teachers who engage in the analysis of examples of effective instruction and student work,
- a content focus,
- coherence and alignment with district policies and practices,
- sufficient duration to allow repeated practice and/or reflection on classroom experiences, and
- collective participation (e.g., by multiple teachers from one grade, school, or department).

The Learning Policy Institute (Darling-Hammond et al. 2017, p. 4) enumerated a similar list of characteristics:

- is content focused,
- incorporates active learning,

- supports collaboration,
- uses models of effective practice,
- provides coaching and expert support,
- offers feedback and reflection, and
- is of sustained duration.

A more recent meta-analysis of nearly 100 studies of K–12 science and mathematics instructional improvement efforts (Lynch et al. 2019) found the following factors most strongly linked to improvements in student outcomes:

- The use of professional development along with new curriculum materials,
- A focus on improving teachers' content/pedagogical content knowledge, or understanding of how students learn, and
- Specific formats, including:
    - meetings to troubleshoot and discuss classroom implementation of the program;
    - the provision of summer workshops to begin the professional development learning process; and
    - same-school collaboration.

These views of professional development highlight the importance of *active teacher engagement*, which can take many forms, including study groups, collaborative group work, and collective engagement in focal tasks. They also emphasize the importance of *focusing on specific content and instructional practices* that have been demonstrated to be effective. And they acknowledge that teachers learn new content and practices in the contexts of their schools and districts, and what they learn needs to resonate and be aligned with policies and practices in their contexts. Many elements identified in the consensus models align with research findings on adult learning (NASEM 2018; NRC 2000).

Several studies in science education offer empirical evidence, using large-scale quasi-experimental research designs, that professional development designed with these principles can improve teacher learning and practice as well as student learning (e.g., Heller et al. 2012; Roth et al. 2011; Taylor et al. 2017; Yoon et al. 2007). This is a relatively small dataset, however, and much of the research informing ideas about quality professional development consists of correlational and small-scale case studies, which often rely heavily on teacher self-report.

It is helpful to understand teacher development as not only an individual issue but also a collective one, relying on mechanisms such as teacher professional learning communities and school-wide supports (NASEM 2015). In fact, research on school improvement suggests that teacher quality is dependent on the school communities that teachers work in, principal leadership, and other factors. This argues for professional learning experiences that include programs outside as well as during the school day and programs that aim to build the capacity of teams of teachers (e.g., Donna 2012; Henderson et al. 2010) or even an entire school's faculty (e.g., Barger et al. 2007), rather than only individual teachers.

Engineering-Related Professional Development

Most research on professional learning opportunities for K–12 teachers of engineering focuses on PD experiences. This makes sense, since, as noted, the bulk of those who teach engineering to

K–12 students have not participated in formal teacher preparation programs but have learned about engineering through various PD experiences. To understand the nature of these experiences and their impact on K–12 educators, the committee conducted a thorough literature review, which yielded 155 relevant articles, 28 from peer-reviewed engineering education journals or book chapters and 127 published in conference proceedings. Below we summarize the findings.[6]

Many of the papers reported on program assessments or evaluations, and it is informative to consider both program characteristics and the different research methods and metrics used to study impact. This kind of analysis can help uncover potentially useful findings as well as reveal gaps and challenges in the research.

Program Characteristics

There was considerable diversity, across a number of dimensions, in the programs described in the literature. For example, educators' learning experiences varied in length and intensity from a few hours or a single day to a week or more. Some PD workshops were repeated at regular intervals for several months or years, while others were a single experience with little follow-up. Some universities have incorporated engineering education graduate certificates in their curricula to provide professional development to current teachers in addition to teacher preparation (e.g., Besser and Monson 2014; Neebel 2015). The teachers who attended these programs tended to be engineering, mathematics, science, or technology teachers, although some programs also recruited school counselors (e.g., Gehrig et al. 2009; Grauer et al. 2013; Inman et al. 2003; Ohland et al. 1996; Rathod and Gipson 1999) or English and social studies teachers (e.g., High et al. 2009; Hunter et al. 2006).

The programs were geographically dispersed across the United States and served small and large groups of educators. The smallest included fewer than five participants, the largest more than 2,000. All grade bands were represented, with some programs serving educators from all grades, just elementary and middle school, or just middle and high school educators. Several programs focused exclusively on elementary, middle, or high school educators.

Although fewer than half of the papers included information about the programs' funding, federal agencies such as NASA (Alemdar and Docal 2011; Alemdar and Rosen 2011; Baguio et al. 2014) and NSF funded many of them.[7] Specific NSF programs supporting K–12 engineering professional development included the Graduate Teaching Fellows in K–12 Education (GK–12), which provided fellowships to allow STEM graduate and undergraduate students to visit K–12 schools[8] (Al Salami et al. 2017; Caicedo et al. 2006); the Math and Science Partnership (MSP) Program, which provided funds for research and development of programs to improve

[6] Two literature searches were conducted: (1) in February 2016 of the databases ERIC (Ovid), IEEE, ProQuest Research Library, Scopus, and Web of Science; and (2) in August 2017 of the American Society for Engineering Education's conference paper database. Both searched as far back as 1998 and used terms such as "engineering education," "engineering in early education," "engineering teachers," "K-12 teachers," and "professional development."

[7] A small number of these programs were funded by companies (e.g., Henderson et al. 2010; Rockland et al. 2013) or state agencies (e.g., Grauer et al. 2013; Pelletier et al. 2006; Schreiner and Burns 2001).

[8] Although the program is no longer active, a description from an earlier solicitation is available at https://www.nsf.gov/pubs/2003/nsf03532/nsf03532.htm.

achievement of all students[9] (e.g., Burghardt and Llewellyn 2006; Burrows and Borowczak 2017; Krause et al. 2008); and the Research Experiences for Teachers (RET) in Engineering and Computer Science,[10] which provides funding to university research labs to host K–12 teachers for a 4-to-6-week summer experience on campus (e.g., Autenrieth et al. 2014; Laffey et al. 2013; Nichol et al. 2017; Yelamarthi et al. 2017). The RET program specifically encourages projects that include teachers from high-need schools and individuals from populations underrepresented in STEM and promotes the inclusion of both K–12 teachers and university students (graduate and undergraduate) in these research experiences. For example, one program developed teams consisting of a tenured engineering or computer science professor, a middle or high school STEM teacher, a STEM faculty member at a community college, an undergraduate STEM-focused teacher candidate, and two undergraduate engineering students. Each team spent six weeks conducting research, participating in professional learning activities, and developing an engineering lesson plan to submit to the TeachEngineering website.[11] Participating team members indicated more teaching engineering self-efficacy as well as better knowledge of engineering careers after their RET experience (Lavelle et al. 2019).

Evaluations of NSF-funded programs show some promising results. For example, high school teachers who attended a one-week professional learning experience and then interacted with GK–12 graduate teaching fellows in science and engineering showed improved attitudes toward interdisciplinary teaching and teaching satisfaction, although middle school teachers in the same program did not show the same improvements (Al Salami et al. 2017). Another GK–12 program paired graduate engineering students with current teachers for a school year and also invited other teachers for a short summer institute taught by the fellows. A follow-up survey indicated that teachers increased their knowledge of engineering content and had greater understanding of what engineers do; many also reported incorporating engineering in their classrooms (Caicedo et al. 2006). One MSP program encouraged professional learning communities for STEM teachers in schools following a summer experience in which they team-taught an interdisciplinary unit and learned about assessing both student knowledge and application of that knowledge (Burghardt and Llewellyn 2006). Another MSP program found that participating teachers improved their attitudes toward interdisciplinary teaching and began to develop labs to demonstrate principles (Krause et al. 2008). RET program evaluations have also shown (often using locally developed measures) that participants increased their confidence and self-efficacy to teach engineering (Ghalia and Huq 2014; Nichol et al. 2017; Ragusa et al. 2014; Trenor et al. 2006), developed greater understanding of engineering (Autenrieth et al. 2014; Barrett and Usselman 2006; Conrad et al. 2007; Georgieva et al. 2013; Kapila 2010), and implemented engineering activities in their classrooms (Barrett and Usselman 2006; Kukreti et al. 2006; Laffey et al. 2013; Trenor et al. 2006). Although the RET program encourages the inclusion of teachers from high-need schools and individuals from populations underrepresented in STEM, most of the published evaluations do not specify that information about the participating teachers. When such information is reported, teachers are in schools with a high proportion of low-income students (e.g., Autenrieth et al. 2014; Nichol et al. 2017) or in urban settings (e.g., Kapila 2010; Ragusa et al. 2014).

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[9] MSP is described at an archived solicitation (https://www.nsf.gov/pubs/2003/nsf03605/nsf03605.htm). A new version of the program includes STEM and computing (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505006).
[10] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505170
[11] https://www.teachengineering.org/

Research Methods and Metrics

Evaluations of these programs took many forms. Although some were conducted by an external evaluator, in many cases it was either unclear who evaluated the program or clear that the director or other program staff performed the evaluation. Most assessments collected descriptive-level data [although some used existing validated scales, such as the Systematic Characterization of Inquiry Instruction in Early LearNing Classroom Environments (SCIIENCE; Molitor et al. 2014) or the Teaching Engineering Self-Efficacy Scale (TESS; Yoon et al. 2014)]; collected both pre- and postdata (e.g., Schnittka et al. 2014); or triangulated information from several sources (e.g., Wang et al. 2011a). Almost half of the evaluations used a mixed-methods design, collecting both qualitative and quantitative data, although most of the data were qualitative. A small number of evaluations compared outcomes between those attending the professional learning experience and a similar group of educators who did not attend (e.g., Rich et al. 2017).

Qualitative data collected included observations of classroom teaching behavior (e.g., using the Reformed Teaching Observation Protocol; Singer et al. 2016), written reflections, open-ended survey responses, interviews, analysis of performance on specific tasks, and examination of artifacts such as lesson plans (e.g., Guzey et al. 2014; Wang et al. 2011a), syllabi, or presentations. Quantitative data included validated scales, concept inventories, and surveys. Qualitative measures are more common among these projects perhaps because engineering education is relatively new and there are fewer standardized measures, with respect to both surveys and observations of instruction available. This makes it more difficult for programs to document change with commonly used, validated measures of teacher attitude, knowledge, or practice.

Program evaluations measured many different variables, including educators' attitudes, behaviors, and knowledge of engineering or of the program they participated in, or student outcomes (e.g., Ragusa 2011). Most metrics relied on participants' self-report (e.g., Henderson et al. 2010), although some evaluations used more objective measures (e.g., concept inventories, classroom observation protocols). Student learning gains were measured with standardized or other content tests (e.g., Macalalag et al. 2010), including for science literacy (Ragusa 2011). Other student outcomes, such as engagement or higher-order skills (e.g., collaboration, communication), relied mostly on reports from the teachers or observations from the providers of the professional learning experience (e.g., Hunter et al. 2010). A few evaluations noted cultural shifts within schools, such as teachers being more open to new ideas and a significantly increased level of collaboration (e.g., Nadelson and Callahan 2014).

Some articles described the formation and sustainability of professional learning communities following the initial experience (e.g., Guzey et al. 2014; Hardré et al. 2013); others described observed or self-reported changes in teaching practices to use more student-centered pedagogies and engineering activities (e.g., Guzey et al. 2014; Kukreti et al. 2015). Several of the evaluations claimed that teachers had (a) improved understanding of engineering, based on either self-report (e.g., LeMire 2015) or a concept inventory test (e.g., Henderson et al. 2010), (b) improved understanding of the engineering research process and how engineering design connects to math and science (e.g., Nadelson et al. 2012), (c) increased engineering skills (e.g., Martin et al. 2015), and (d) increased engineering pedagogical content knowledge (self-assessed; e.g., Head and Hynes 2011; Webb 2015).

Although a few examined outcomes for students (e.g., Hunter et al. 2010; Macalalag et al. 2010; Ragusa 2011) or schools, the most commonly measured outcomes for participating educators related to increasing their own engineering literacy with the expectation that teachers could then develop it in their students. However, some programs aimed to promote literacy about engineering careers (Brophy and Mann 2008; Gehrig et al. 2009; Grauer et al. 2013) or encourage STEM integration (e.g., Al Salami et al. 2017; Wang et al. 2011a) and college and career readiness (e.g., Bowen 2016; Crawford et al. 2012; Nadelson et al. 2014; Steimle et al. 2016).

Self-Efficacy and the Growth of Educator Expertise

Because attitudes, beliefs, and self-efficacy affect teaching behavior (Shulman 1986), and because aspects of self-efficacy are discipline-specific (Yoon et al. 2014), many engineering professional learning programs explicitly assess changes in those areas. Teachers' relative lack of knowledge and understanding of engineering (e.g., Cunningham et al. 2006), especially compared to math or science, can lead to negative attitudes toward engineering as well as a lack of confidence in, or even fear of, teaching engineering (Culver 2012; Lachapelle and Cunningham 2014). This fear can be overcome, however (box 5-7).

BOX 5-7
Overcoming Teachers' Fear of Engineering

After I led one of my first professional development sessions for elementary educators, a 3rd-grade teacher approached me to confess that she had almost skipped the workshop. She had not been able to sleep the previous night as she was trying to envision how she could possibly teach engineering to her students. "If science is scary, engineering is terrifying," she said. She had no idea what engineering might look like with young children and she had no background in the discipline itself. This was not the first time someone had shared these fears; I witnessed this initial trepidation often. However, the teacher did assert that she was glad she came to the workshop, despite her anxiety: "Now that I understand what engineering looks like for children, I see how it can work in my classroom and how engineering will benefit my students. I can do this. They can do this!"

One barrier that many teachers face to including engineering in their classrooms is their fear of teaching a new subject. Many teachers have never taken a course in engineering and because the K–12 classes they attended did not include engineering ideas or activities they have no models to reference. Understandably, the idea of introducing this unfamiliar discipline to a classroom full of students can be fear-provoking and intimidating, especially for a discipline like engineering which evokes stereotypical perceptions of super-rigorous, highly quantitative study. How can such fear be overcome?

Introducing educators to engineering activities can help them to visualize what age-appropriate engineering looks like. Engineering with six-year-olds is not the same as engineering with college students—appropriate activities consider central tenets of engineering but modify these to take into account the physical, cognitive, social, emotional, and language capabilities of students. High-quality professional development sessions and K–12 engineering curricula can demonstrate how engineering ideas might be translated for students of various ages. Participating in engineering activities as their students will provides a safe space for teachers to build their own knowledge of engineering. De-briefing the activities through the lens of the student learner and then through the lens of a teacher helps educators to think about various facets and learning objectives of the engineering lessons and to develop comfort with the hands-on activities and facilitation strategies.

Teachers tell me that access to, or interaction with, other colleagues can help mitigate fears related to engineering. Hearing about engineering experiences, challenges, pathways, and suggestions from more experienced peers can be comforting, motivating, and inspirational. Time to connect with supportive colleagues to plan or debrief engineering lessons is helpful. The opportunity to think through potential stumbling points they might encounter related to engineering and to brainstorm implementation strategies help teachers feel more prepared.

Access to other teachers' expertise does not have to occur face-to-face or even in real time: classroom videos that capture the engineering lessons being enacted with teachers in real classrooms provide opportunities to see and study how others professionals shape their lessons, guide their students, and prompt teams or individuals to work through challenging situations. Teachers appreciate models of pedagogical strategies that work with students. Testimonials about their experiences with engineering from educators who work with similar populations of students can also bolster beginning teachers' courage to try this new discipline with their pupils.

Finally, teachers tell me that their students' responses to engineering activities propel them to work through the initial rough spots to hone their engineering instruction. They find that students are often more engaged in engineering activities than other school activities. Students, oftentimes those who have not been motivated by other school activities, are highly engaged by engineering challenges and demonstrate creativity and leadership. Engineering challenges can inspire underperforming or hard-to-reach students. This sort of student reaction, along with their excited pleas, "Can we do engineering today?" convinces hesitant teachers that their initial forays into engineering are reaching their pupils and encourages them to grow their knowledge of engineering and their repertoire of pedagogical strategies.

SOURCE: This vignette was written by Christine Cunningham, Pennsylvania State University, founder of the Engineering is Elementary curriculum. Elements of the vignette were taken from *Engineering in Elementary STEM Classrooms* (Cunningham 2018). Printed with permission.

Perceptions of engineers and engineering work, whether accurate or inaccurate, can affect the likelihood that teachers will implement engineering activities in the classroom (Yasar et al. 2006). Teachers and future teachers may also lack confidence in both their STEM content knowledge and their ability to teach engineering (Culver 2012). The self-efficacy of many science teachers to teach about engineering is quite low (box 5-8).

BOX 5-8
Science Teachers Self-Efficacy to Teach Engineering

In a national survey, Banilower and colleagues (2018) asked middle and high school science teachers how prepared they felt to teach three concepts in engineering: defining engineering problems, developing possible solutions, and optimizing a design solution. Fewer than 15 percent of teachers at either level felt very well prepared, while more than a quarter said they were not adequately prepared. In general, middle school teachers felt more prepared than high school teachers. Although Banilower and colleagues (2018) did not ask elementary teachers to indicate how prepared they felt to teach specific engineering concepts, when asked how prepared they felt to teach engineering, over half (51 percent) said they were not adequately prepared and only 3 percent said they felt "very well prepared." Another 33 percent felt somewhat prepared and 14 percent felt fairly well prepared.

Most results reported by PD programs described improvements in attitudes, positive changes in behavior, and/or increases in knowledge. For example, many programs found more positive attitudes and beliefs about engineering, including the importance of connecting it to topics in science and math classes (e.g., Al Salami et al. 2017). Others noted that teachers had increased confidence (e.g., Curtis et al. 2016; Henderson et al. 2010; Sargianis et al. 2012) and decreased anxiety about teaching engineering in their classrooms. Teaching self-efficacy, assessed through self-report but also with validated scales (e.g., box 5-9), also improved following some programs (e.g., Head and Hynes 2011; Wang et al. 2011b; Webb 2015).

BOX 5-9
Measuring Self-Efficacy

Although not widely cited in the literature, two scales for measuring teaching engineering self-efficacy (TESS; Yoon et al. 2014) and engineering design self-efficacy (Carberry et al. 2010) have been designed. The TESS consists of 23 total questions in four subscales that measure self-efficacy for engineering pedagogical content knowledge, outcome expectancy, engagement, and disciplinary (i.e., managing student behavior). Yoon and colleagues (2014) examined the content and face validity of the TESS using structural equation modeling and item analyses. The engineering design scale consists of 36 questions that ascertain motivation and anxiety about performing engineering design activities as well as self-efficacy and outcome expectations individuals have about engineering design. Carberry and colleagues (2010) gathered evidence to show content, criterion, and construct validity of the instrument.

Elementary teachers who participated in a year-long program that included 45 minutes of professional learning each week on computing and engineering in K–12 education increased their self-efficacy to teach these subjects compared to teachers from a similar school who did not participate, although both groups of teachers had similar self-efficacy for teaching math and science. Because one source of self-efficacy is a mastery experience (e.g., Bandura 1997), the teachers who implemented an engineering activity in their classroom and notice positive results increased their self-efficacy for teaching engineering even when the activities they implemented were simple (Rich et al. 2017).

Lee and Strobel (2014), using a Concern-Based Adoption Model (Anderson 1997), examined teachers' anxieties about and use of K–12 engineering before and after attending a PD program and found that they evolved during the program. Before the program, teachers were primarily focused on learning about engineering education, its demands on their teaching and time, the logistics of implementing engineering, and student outcomes. After participation, many of those worries had lessened, but teachers still had questions about impacts on students and wondered how to work with others in their school to implement engineering and how to determine its benefits for the school, teachers, and students. That is, as teachers acquired more information, their concerns changed from a personal focus (e.g., learning about engineering and what they need to teach it) to a focus on others (e.g., impact on student outcomes and how teachers could work together to best teach engineering), suggesting a need for continuing support as teachers implement engineering (Lee and Strobel 2014). Teacher leaders in K–12 engineering may be an important source of support for less-experienced educators (e.g., NASEM 2017, pp. 12–14).

A small body of research has documented the challenges associated with preparing teachers to teach engineering. Using data collected from interviews and survey responses from 73 elementary teachers who participated in a week-long engineering PD experience, Sun and Strobel (2013) developed a model of adoption of engineering education that is directly related to how practical and sustainable teachers think the engineering instructional goals and materials will be. The researchers also note that as teachers' confidence in and comfort with teaching engineering increase, the likelihood that they will implement engineering in their classroom also increases. A third factor influencing adoption is whether teachers believe that students benefit from learning engineering and if so how. Teachers who think of simple and limited benefits like knowing terms or having fun are less likely to teach engineering than those who appreciate that students will develop problem-solving and critical-thinking skills in addition to becoming familiar with engineering as a field of study or a career. Finally, the approach to incorporating engineering in the classroom affects implementation; teachers who view an engineering activity or lesson as isolated from their other teaching are less likely to adopt than those who purposefully connect engineering to other topics they teach.

Similarly, three factors are related to the development of expertise in elementary engineering education. Teachers with a low level of expertise tended to present engineering lessons or concepts exactly as they learned them in their PD experiences without relating them to the context of their own classroom or their students' lives. On the other hand, with greater expertise, teachers adapt lessons and activities to real-world contexts that students understand and relate to. Second, as teachers acquired engineering PCK, they increased their expertise, began to overcome problems such as student frustration with the engineering design process or group work, and eventually created lessons that provide active learning experiences for the students. Finally, teachers began to connect engineering to their teaching in other disciplines as their expertise grew (Sun and Strobel 2013).

Diefes-Dux (2014) proposes a four-stage model for the implementation of elementary engineering education, beginning with PD experiences that help educators overcome unfamiliarity with and fear of engineering. However, even with increased comfort with and excitement about engineering, the first year of implementing engineering activities in the classroom often runs into barriers such as time constraints for preparing and incorporating lessons in the classroom, lack of awareness of and support for engineering education from colleagues and administrators, and beliefs about student learning. Thus, initial implementation of engineering activities is disconnected from the rest of the curriculum and does not connect students to broader knowledge of engineering. After that first-year experience, teachers may seek more PD opportunities in order to better connect engineering to other subjects and learn more about engineers and engineering. Finally, if they have support from the education system, including peers and administrators, teachers' second-year engineering implementation better integrates with other subjects and promotes student learning. (Chapter 6 considers more fully the importance of systems of support for teacher professional learning.)

Potentially Effective Practices

Several professional learning experiences described in the literature include some features described earlier (Darling-Hammond et al. 2017; NASEM 2015) that are associated with high-quality professional development and so may deserve to be considered as potentially effective practices for building educator capacity in K–12 engineering education.

Curriculum design-based professional development can provide educators with both engineering content knowledge and an active learning experience. One program using this approach brought together teachers for six months to create and get feedback on student activities, lesson plans, and assessments. Participating teachers believed that the program increased their engineering knowledge (measured retrospectively), improved their self-efficacy for engineering curriculum design (measured three times with a scale), and produced curricula that addressed standards and integrated knowledge from engineering and other disciplines (Berry 2017; Berry and DeRosa 2015).

An NSF-funded program at the University of Cincinnati provided professional development of sustained duration to middle and high school teachers so they could teach engineering to their students, with the goal of both improving student performance in science and mathematics and increasing student awareness of STEM majors. Teachers spent seven weeks during two consecutive summers learning foundational engineering and design principles, as well as applications of engineering to math and science topics. Some of the professional learning courses were taught by university engineering faculty, others by high school teachers experienced in K–12 engineering education. Program evaluations showed that while all courses improved the teachers' self-report of knowledge and skills related to engineering, high school teachers with more experience in and knowledge of how the K–12 educational system works were viewed as more effective instructors (Rutz et al. 2015).

Professional development that brings together teachers from mathematics, science, and technology to form learning communities can support efforts to teach engineering in an integrated fashion. Donna (2012) documents a program in which interdisciplinary teams complete an engineering design activity intended to promote both content and pedagogical knowledge. Team members discuss how the activity connects engineering to concepts in mathematics, science, or technology, and they consider how it could be used as a pedagogical tool with students in other STEM classes.

Many engineering PD experiences are of relatively short duration, so an online community of practice can support teachers as they implement what they learned. Although teachers cite lack of time as a barrier to participating in such a community, access to teaching and learning resources (Forbes et al. 2017) and the ability to hold discussions and receive feedback from peers help them as they begin to teach engineering (Liu et al. 2012). At least two engineering-focused online communities provide resources and other supports for K–12 educators: the LinkEngineering Educator Exchange (linkengineering.org), a project of the National Academy of Engineering, and TeachEngineering (teachengineering.org), overseen by a coalition of postsecondary institutions. Although together the two sites provide hundreds of resources and are visited by thousands of teachers each month, neither has been empirically evaluated for its effect on teachers' knowledge of and confidence to teach engineering.

Encouraging Culturally Responsive Teaching

As noted earlier in the chapter (box 5-4), culturally responsive teaching is important for all educators and especially for those engaged in introducing students to engineering. The committee could find only one example from the literature addressing this important challenge. The program infused technology and engineering concepts in science and mathematics professional development for teachers working in American Indian schools in Utah. A key component was the creation of advisory groups of Native community members to help develop and provide culturally relevant professional learning experiences for the teachers (Becker et al. 2009). Teachers were exposed to the idea that traditional educational experiences are based in the community of the students and often involve children and their parents as well as elders and other community members.

CONCLUSION

The committee found no definitive, empirically tested answer to the question of what engineering knowledge and practices K–12 teachers of engineering need. Sources we examined, such as the standards by Farmer and colleagues (2014), suggest that researchers and practitioners have made initial progress delineating important but general areas for the preparation of these educators. Far less progress has been made investigating how the knowledge base differs for teachers of different grades, how knowledge builds on itself over time (progression), what specific preparation in science and mathematics teachers of engineering should have (and how this preparation might vary according to grade and primary subject taught), how this preparation might differ from that needed by technology teachers, or how to test the preliminary conceptions of teacher knowledge empirically. It is notable that the bulk of research reviewed by the committee related to both the preparation of K–12 teachers of engineering and PD for these educators is focused at the elementary level. This may in part reflect the fact that, unlike most secondary educators, elementary teachers are responsible for teaching multiple subjects, often including science. Thus in some ways elementary classrooms may be better suited to the introduction and study of more integrative approaches to teaching.

Research on teaching in general and on teaching in specific subjects, such as science, strongly suggests that pedagogical content knowledge is important to teacher effectiveness, and there is every reason to believe the same is true for teachers of engineering. However, there is scant information in the literature about the potential landscape of engineering teachers' PCK. What few clues have been unearthed, related to engineering design, for example, do not appear to have been tested empirically to determine their validity. Knowledge of and skill in teaching diverse students through the use of more inclusive pedagogies seem to be essential elements of the professional knowledge base for teachers of engineering, whether the goal is general engineering literacy or more advanced understanding and skill in the domain.

The committee also found no empirically tested answer to the question of what learning opportunities K–12 teachers of engineering will need. Research on quality teacher preparation, induction, and professional development in other subject areas suggests that these learning experiences improve teachers' subject matter knowledge and PCK and correlate with student performance; it is reasonable to assume that engineering learning experiences would lead to similar improvements. The committee's review of the literature describing engineering-specific teacher learning experiences uncovered some evidence that such professional learning can lead to improvements in teachers' self-efficacy to teach engineering, attitudes toward engineering, and knowledge of the engineering design process and concepts. However, there is little research connecting those learning experiences to classroom teaching behavior or student outcomes. The growing number of programs of teacher preparation and PD experiences for K–12 teachers of engineering suggests that there are many opportunities for important research to be conceptualized and conducted.

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6

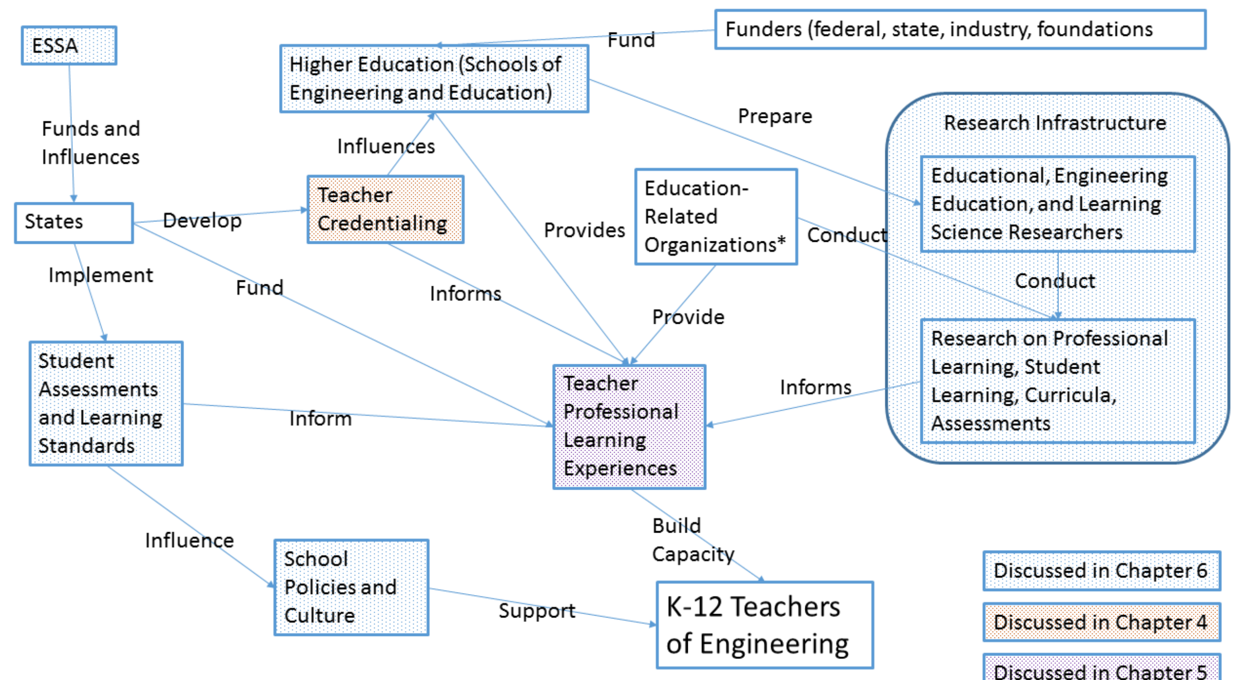
Creating a System of Support for K–12 Engineering Teachers

Building the capacity of K–12 teachers of engineering depends on a complex system of interrelated components. (One version of such a system appears in figure 6-1.) Components include state boards of education, federal and state education agencies, funders, industry, and education-related organizations (e.g., professional societies, out-of-school-time learning institutions, nonprofits). The interconnections among these and other entities may be thought of as an ecosystem (e.g., NRC 2014a) that affects the preparation and support of teachers of engineering in various ways.

For example, individual teachers, schools, districts, and even states can partner with outside organizations to support high-quality teacher professional learning in engineering. Out-of-school-time institutions can partner with teachers to bring engineering into the classroom or can engage teachers in design activities. Cultural and community organizations can provide space, materials, design challenges, or other support for teachers to implement engineering. Professional societies can develop or expand programs and inducements that encourage precollege educators to become members and take advantage of opportunities for professional development at national or regional meetings or through online learning experiences. Finally, many US industries employ engineers at various levels of corporate structures and in recent years some companies have stated a willingness to become more active in STEM education in their communities by providing funding for equipment or supplies needed for engineering activities, classroom visits by working engineers, or both.

Partnerships can benefit efforts to prepare teachers to teach engineering, but only under the conditions of mutual respect and an openness to learning by all partners (Diefes-Dux 2014). For example, while engineers have expert knowledge of the field, they have little knowledge of either the culture of a K–12 school or professional knowledge for teaching. Thus, teachers and engineers can each contribute their expertise in an environment with multiple opportunities for ongoing teacher professional development, ongoing revision and adaptation of created instructional materials, and an intentional effort to create learning experiences for diverse teacher and student audiences, including but not limited to rural, suburban, and urban contexts and traditionally underrepresented groups in STEM.

FIGURE 6-1 A Systems View of Quality Preparation of K–12 Teachers of Engineering



* e.g., professional societies, non-profit organizations such as Achieve

It is important to note that a systemic approach to effective teacher preparation and support, as with other educational transformation, requires sustained work across many elements of the system. Principles proposed (NRC 2015) to guide state implementation of the Next Generation Science Standards (NGSS; NGSS Lead States 2013) are instructive:

- Make certain that the system aligns at the horizontal (curricula, instruction, assessment, professional learning), vertical (classroom, school, district, state), and developmental (grade band) levels.
- Form teams at the district and school levels that include administrators, teachers, and researchers who have the support needed to implement changes. Teacher leaders, in this case those who have expertise in teaching engineering at the K–12 level, are critical to the work of these leadership teams.[12]
- Collaborate and share information across multiple levels—state, district, school, individual teachers.
- Recognize that time will be needed to develop new materials and assessments and build the knowledge base and skills of teachers.
- Prioritize equity and inclusion across the system.
- Develop effective communication across the system that ensures all stakeholders understand priorities and plans.

[12] The category of teacher leader encompasses many different roles within a school or district, such as "lead teacher, curriculum specialist, mentor, collaborating teacher, instructional coach, professional development leader" (NASEM 2015, p. 85). They perform a variety of tasks: "instructional support (e.g., observing and giving feedback to teachers), communications (e.g., sharing information from district level to teachers), school administration (e.g., selecting instructional materials or evaluating teachers), and general administration (e.g., organizing and managing instructional materials)" (Schiavo et al. 2010, p. 2).

Although it was beyond the committee's scope to consider all aspects of the broader ecology that shapes preparation of K–12 teachers of engineering, in this chapter we consider five components not already discussed in the report that we believe have the greatest potential to affect K–12 engineering education:

1) Federal legislation governing elementary and secondary education
2) State policies around learning standards and assessments
3) School and district policies and culture
4) Higher education
5) Research infrastructure.

FEDERAL LEGISLATION

The primary legislation governing federal investments in K–12 education is the Elementary and Secondary Education Act (ESEA). The current version of ESEA, the Every Student Succeeds Act (ESSA)[13], authorizes funding through the 2020–21 school year for a number of programs and initiatives, many of which the states are expected to design and carry out. For the purposes of this study and consistent with the focus of this chapter, the most critical elements of the law address the preparation of K–12 STEM teachers, credentialing options for these educators, and the development of statewide student assessments in science. State assessments of student achievement (described in the next section) are an important component of the education system, because they can influence the emphasis that districts, schools, and teachers must place on particular subjects.

ESSA offers the option for states to receive funds for the development and implementation of professional learning experiences and "other comprehensive systems of support for teachers, principals, or other school leaders to promote high-quality instruction and instructional leadership in science, technology, engineering, and mathematics subjects, including computer science."[14] In addition, as noted in Chapter 4, requirements for becoming certified as a teacher of engineering vary across states but may include alternative certification. Although the committee found no evidence of formal efforts to provide alternative routes to certification for K–12 teachers of engineering, ESSA allows states to expand or improve programs for alternative certification, including in engineering.[15]

STATE POLICIES

State education policies, programs, and practices can support efforts to make engineering a better-integrated component of the K–12 curriculum, including by prioritizing state or district funding for professional learning opportunities. Supportive practices might also include informed decision making about the extent to which a state will embrace and implement recommendations about the role of engineering in K–12 education that have been published in national standards

[13] https://www.ed.gov/essa
[14] See https://legcounsel.house.gov/Comps/Elementary%20And%20Secondary%20Education%20Act%20Of%201965.pdf, p. 157 (xvii).
[15] Part A—Supporting Effective Instruction, Sec. 2101 [20 U.S.C. 6611] Formula Grants to States, (c) State Use of Funds, (4) State Activities, (B) Types of State Activities, (iv).

documents and about how learning in this subject is assessed. On the other hand, policies can hinder K–12 engineering education by not funding professional learning or incorporating engineering in state standards. State boards of education, which often approve which textbooks school districts are allowed to purchase with state funds, influence what content will be taught and thus can promote or ignore engineering.

State Standards

Subject-specific content standards have been a key driver of US K–12 education reform since the early 1980s, prompted in part by US students' poor performance on international comparative assessments of achievement (e.g., USDoEd 1983). State curriculum standards are often based on standards documents developed at the national level through a consensus process involving input from multiple stakeholders. There are no standalone standards for K–12 engineering but, beginning in the late 1990s, a handful of states included engineering-related learning goals in their science standards (Carr et al. 2012). More recently, *A Framework for K–12 Science* (NRC 2012) and the resulting *Next Generation Science Standards* (NGSS Lead States 2013) have called for even closer ties between the teaching and learning of science and engineering with an emphasis on students learning about both subject domains through active practice rather than passive exposure. According to the National Science Teaching Association (NSTA), 20 states and the District of Columbia, representing 41 percent of all US K–12 students, have adopted NGSS; 22 additional states, representing another 43 percent of students, have developed their own standards based on recommendations in the NRC *Framework* (NSTA 2019).

All of the aforementioned documents elucidate principles and standards for integrating engineering and science. In contrast, the International Technology and Engineering Education Association (ITEEA) has published standards for engineering and technology as stand-alone subjects and has revised those standards twice, with the latest version released in 2007.

The existence of standards, by itself, does not lead to meaningful or lasting changes in education. For that to happen, standards must be not only adopted (or adapted) but also implemented. And the translation of national standards into practice occurs at the state and local levels. Standards implementation requires coordinated effort across many components of the education system, including curriculum, assessment, and teacher professional learning, over an extended period.

Assessments of Student Learning

Accountability provisions of ESSA require states to assess student achievement in English language arts and mathematics (yearly from grades 3 to 8 and again once in high school) and science (once per grade band). States must report these data yearly to the federal government. Schools can be punished for not making adequate progress toward achievement goals, and this creates pressure to focus classroom instruction on the topics to be tested (Darling-Hammond et al. 2016).

Historically, assessments for accountability have probed student recall of concepts in a single school subject area, rather than requiring students to connect ideas across two or more subjects (NAE and NRC 2014). As NGSS implementation proceeds in the adopting states, science assessments presumably will need to measure more complex learning outcomes, in keeping with the standards' performance expectations that combine practices, crosscutting concepts, and core disciplinary ideas in science and engineering (NRC 2012). Thus, students will be expected to solve problems by applying their knowledge and skills rather than choosing the correct answer from a list of possibilities. This approach will increase the amount of time needed for assessments and suggests a need for a broad assessment system that includes both formative and summative tests that can be used for both classroom performance and state-mandated assessment (NRC 2014b; Osborne et al. 2015).

The committee could not determine how many states are working toward these new accountability tests. Some federal grants encourage the development of state science assessments that fit with NGSS standards (O'Keefe and Lewis 2019). Under ESSA, states may use federal dollars to integrate engineering design skills and practices in their science assessments, but they are not required to do so.[16] One knowledgeable expert who has responsibility for assisting states grapple with NGSS-related assessment indicated very few states are incorporating engineering in a meaningful way (personal communication, A. Badrinarayan, Achieve, 8/30/19).

The National Assessment of Educational Progress (NAEP) assessment of Technology and Engineering Literacy (TEL; see chapter 3) provides a high-level indicator of eighth-grade students' understanding of engineering and technology concepts and their ability to solve scenario-based design challenges. Unlike the ESSA-driven statewide tests, TEL is a "low-stakes" assessment. It is administered only every four years (2014 and 2018, thus far) and, because of its sampling methodology, cannot provide results at the level of individual students, classrooms, or schools. The assessment is therefore unlikely to spur state education leaders to prioritize support for the preparation of K–12 teachers of engineering.

SCHOOL AND DISTRICT POLICIES AND CULTURE

At the local level, school and district policies are influenced by state and national standards, providing opportunities for educators to craft local procedures that they have ownership of and that are aligned with other education levers (teacher professional development, teacher evaluation, student assessments). Achieve Inc., which coordinated the state-led effort to create NGSS, has developed various guidance documents to assist states and districts in the standards-implementation process. One such publication, the 2013 *NGSS Adoption and Implementation Workbook*, poses questions intended to help education leaders think critically about the conceptual shifts required to implement the standards, including questions related specifically to the integration of science and engineering (box 6-1).

BOX 6-1
Questions Relevant to the Integration of Science and Engineering in NGSS

- Do our current science standards require students to use engineering design ideas and practices alongside the traditional science disciplines from kindergarten through grade 12?
- How comfortable are our current and candidate science educators with engineering design? Do they raise it to the same level as scientific inquiry as a core practice in science instruction? Do they give core ideas of engineering and technology equal weight with those in other disciplines?

[16] Part B—State Assessment Grants, Sec. 1201, [20 USC 6361], Grants for State Assessments and Related Activities, (a) Grants Authorized, (2), (G).

- Do our schools and support systems prepare our educators to teach engineering design and the core ideas of engineering and technology? Is this reflected in policy/funding for course offerings and their content?

SOURCE: Achieve and USEDI (2013), p. 34.

More recent guidance from Achieve (2017), directed at school and district leaders, proposes 13 indicators that can be used to judge the success of efforts to implement NGSS. Engineering is specifically called out in just one of the indicators, related to assessments, and then only as one of eight recommended actions. The limited attention to engineering in this document, particularly when compared with the issues raised by the questions in box 6-1, suggests to the committee that there is considerably more that needs to be done to educate and support local and district education leaders about how to make engineering a meaningful part of NGSS implementation.

School culture also affects preparation to teach engineering. Principals who are knowledgeable and supportive of STEM will empower teachers to increase their knowledge and skills for teaching engineering, especially if they include teachers in decisions about STEM in the classroom (Nadelson and Callahan 2014). One form of support is the development of professional learning communities of teachers who are experimenting with new materials and new approaches to instruction and can support each other as they implement educational innovations. These professional learning communities can be within one school, conducted as follow-up for a professional development program (e.g., Hardré et al. 2013; High et al. 2009), or conducted online (e.g., Liu et al. 2009).

Teachers who have experience using engineering activities to engage their students and improve their performance on both classroom and state assessments might provide critical leadership to both school administrators and other teachers as they gain the skills and knowledge to implement engineering. These teacher leaders, who promote change from within the school and district governance structures, can help support professional learning in engineering for other teachers and can also shape policies at the local level (NASEM 2017).

HIGHER EDUCATION

Postsecondary institutions play a major role in supporting current and preparing new K–12 teachers. Disciplinary departments offer courses that enhance content knowledge of prospective and practicing teachers; schools of education offer courses and programs for initial and on-going certification and licensure.

One source of engineering content expertise for K–12 teachers of engineering is postsecondary engineering education programs, housed in both schools of engineering and schools of engineering technology (ET; box 6-2). To the committee's knowledge, apart from the small number of engineering colleges participating in the UTeach[17] program and a handful of other programs (see chapter 4, Professional Learning Experiences for K–12 Teachers of Engineering, and chapter 5, Teacher Learning Opportunities), no engineering or ET schools are involved in the preparation of prospective teachers of engineering.

BOX 6-2

[17] Additional information is available at www.uteachengineering.org/.

Engineering Technology Education

Unlike engineering, engineering technology (ET) is unfamiliar to most Americans and goes unmentioned in most policy discussions about the US technical workforce. Yet workers in this field play an important role in supporting the nation's infrastructure and capacity for innovation.

The emergence of ET as an academic discipline can be traced to the mid-1950s, when curricula in traditional engineering programs began to focus more heavily on advanced science and mathematics coursework. The resulting deemphasis on student hands-on laboratory work contributed to the establishment of the first 2-year (associate's degree) ET programs, which were designed to ensure that the engineering team included individuals skilled in application as well as theory (Henninger 1959). Four-year (bachelor's degree) ET programs, which first appeared in the 1960s, also had a distinct focus on application.

The number of degrees awarded in engineering technology, while smaller than in engineering, is substantial. In 2014 there were 17,915 graduates with 4-year ET degrees and 34,638 with 2-year ET degrees in the United States, according to the Department of Education's Integrated Postsecondary Education Data System. By comparison, in that same year, there were 93,950 graduates of 4-year engineering programs and 4,409 graduates with 2-year engineering degrees. In 2014, US schools, mostly community colleges, awarded 49,217 subassociate's-degree certificates in ET.

SOURCE: Adapted from NAE (2017), pp. 1–2.

Two cohorts of engineering schools may have special incentive to consider a role in teacher preparation. One is the roughly 100 engineering schools that have expressed strong interest in and agreed to grant college credit for a potential new high-school engineering course that could become part of the Advanced Placement offerings of the College Board (see chapter 1). The second is the small group of universities (box 6-3) that have established graduate departments of engineering education, many of which conduct research on issues relevant to teaching engineering at the K–12 level.

BOX 6-3
Universities with Graduate Schools or Departments of Engineering Education

University of Buffalo
University of Cincinnati
Clemson University
Florida International University
University of Florida
University of Georgia
Louisiana Tech University*
University of Michigan**
University of Nebraska–Lincoln
North Carolina State University***
The Ohio State University
Purdue University
University of Texas at El Paso
Utah State University
Virginia Tech

* Offers a PhD in engineering with an engineering education concentration.
** Offers a PhD in engineering education research.
*** Offers a PhD in engineering and technology education.

SOURCE: Carberry (2019).

Expanding and improving teacher preparation programs may require engineering programs and schools of education to collaborate. Chapter 5 describes several such collaborations. Students who take engineering and education courses as well as courses offered by other university departments or schools may have difficulty scheduling classes, labs, and times for design teams to meet, particularly because the respective departments have not traditionally communicated well (Zarske et al. 2017). In addition, engineering credit loads are typically higher than for other majors, thus making adding other curriculum elements more challenging. This suggests that effective partnerships to provide engineering-specific curricula to teacher candidates will require planning and cooperation across multiple schools or departments. However, many engineering schools have struggled to implement changes to their own pedagogy and curriculum, and because faculty need to emphasize technical research as part of the promotion and tenure process (Matusovich et al. 2014), even those who value the idea of teaching engineering content to prospective K–12 teachers may be reluctant to add to their workload (Besterfield-Sacre et al. 2014). These barriers will need to be taken into account for collaborations to work.

Undergraduate engineering programs have evolved to incorporate more design and problem-based learning courses earlier (e.g., Fortenberry et al. 2007) or throughout (e.g., Pierrakos et al. 2012) the curriculum, with the necessary mathematics and science concepts taught either concurrently with those courses (e.g., Pierrakos et al. 2012) or integrated within the courses (e.g., Carlson and Sullivan 2004). Some institutions include prospective K–12 teachers in those courses. For example, the Engineering Plus curriculum described in Chapter 4 provides flexibility for students interested in both an engineering degree and a secondary education teacher certification (e.g., Salzman et al. 2018; Zarske et al. 2015, 2016). As described in Chapter 5, several institutions require at least one engineering design course for all elementary education majors (e.g., Bottomley and Osterstrom 2010; O'Brien et al. 2014) to prepare them for implementing engineering in their K-8 classes.

Chapter 4 noted that current national standards guiding K–12 science teacher preparation include mention of engineering. Yet the committee could find no hard data regarding the extent to which science teacher education programs are integrating engineering ideas and practices in their curricula.

US schools of engineering and industry also provide engineering-focused professional development experiences for K–12 educators, such as workshops and summer institutes; some of these were described in chapters 4 and 5. Engineering-related curricula and professional learning experiences were also developed by recipients of NSF's Research Experiences for Teachers (RET) in engineering and computer science,[18] which allow local K–12 teachers to experience engineering research firsthand and support teachers as they develop curricula based on that research. (Data on the impacts of RET programs are discussed in chapter 5.) Research-based engineering-related curricula and professional learning experiences were also developed by some recipients of NSF's Math and Science Partnership program, many of which involved collaborations between higher education institutions and local school districts.[19] In addition to workshops and other professional development experiences (e.g., Berry and DeRosa 2015), local

[18] Information is available at https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505170.
[19] Although the MSP program is no longer active, many resources developed by its grantees are available at http://hub.mspnet.org/.

companies have provided summer externships for teachers to allow them to experience engineering in a workplace and apply that experience to their teaching behaviors (e.g., Bowen 2016).

RESEARCH INFRASTRUCTURE

Education, social science, and learning science research can lead to improvements in how teachers are prepared and supported throughout their careers. For example, research has contributed to evidence-based curricula for engineering. In addition to the curricula developed through collaborations with higher education researchers (e.g., through RET or MSP funding), some engineering curricula such as Engineering is Elementary have attempted to map components of their programs to national and state standards in science.[20]

Research has also influenced classroom assessments of student achievement (e.g., Darling-Hammond et al. 2016; NRC 2006, 2014, 2015; Osborne et al. 2015). Formative and summative classroom assessments of student achievement in engineering depend on whether the engineering activities evaluated are presented as standalone lessons or integrated in larger STEM activities (NAE/NRC 2009), but because most assessments focus on single topics, integrated STEM activities will need new classroom assessments (NAE and NRC 2014). Some independent research groups have developed NGSS-aligned classroom tasks with accompanying assessments. Achieve, Inc. has developed several classroom assessment tasks that include integrated science and engineering tasks, and it encourages teachers to continue to improve them.[21] The Stanford NGSS Assessment Project (SNAP[22]) conducts research, provides assistance to educators and those who provide professional learning experiences, and develops performance assessments, including for engineering, that support implementation of NGSS in states that have adopted the standards. The Next Generation Science Assessment,[23] a collaboration of experts in engineering and science education, assessment, learning, and instruction, also develops NGSS-aligned assessments that include engineering design. However, these task-based assessments for engineering practices and concepts are not as numerous as those for other subjects (Wertheim et al. 2016), and it is also not clear how many teachers of engineering know how, or are developing their capacity, to use them appropriately, let alone design such assessments for their own classes.

As noted throughout the report, the evidence base that might inform effective approaches to preparing K–12 teachers of engineering is thin and uneven. There are a number of reasons for this deficit, including the fact that engineering is relatively new as a K–12 subject. Another important factor is the size and capability of the research workforce. It is the committee's impression, based on personal knowledge and experience, that there are few education or social science researchers and learning scientists studying issues relevant to K–12 engineering. This is likely true absolutely as well as in comparison to the number who study teaching and learning in the other STEM subjects. Although growing, the field of engineering education research is still relatively small; few engineering educators have the training and experience needed to conduct quality education research, and of those who do, their focus tends to be on postsecondary engineering.

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[20] For additional information see https://eie.org/eie-curriculum/eie-connects-state-science-standards.
[21] https://www.nextgenscience.org/classroom-sample-assessment-tasks.
[22] https://snapgse.stanford.edu/
[23] http://nextgenscienceassessment.org/

Funding for K–12 engineering education research exists, but generally at lower levels than for research on other STEM subjects. As an example, between 2014 and 2019 the National Science Foundation (NSF) made 369 awards totaling almost $550 million in the Discovery Research PreK–12 program (DRK–12[24]), which promotes research on teaching and learning in preK–12 STEM education. Of those awards, only 23, totaling just over $30 million, focused on engineering education.

However, the research infrastructure continues to grow. As mentioned, several colleges of engineering have departments of engineering education that train engineering education researchers. Purdue University's School of Engineering Education houses the INSPIRE Research Institute for Pre-College Engineering,[25] with approximately 20 researchers at the faculty, staff, or postdoctoral levels and another 75 or more at the graduate and undergraduate levels. These researchers examine topics related to the integration of engineering with other school subjects, broader participation in engineering, and engineering mindsets in K–12 education. Purdue University also publishes the *Journal of Pre-College Engineering Education Research* (*J-PEER*), an open-access, peer-reviewed journal that that was launched in 2011 and is dedicated solely to research in K–12 engineering education.

Many professionals in the engineering education and engineering education research communities are represented by the American Society for Engineering Education (ASEE), which has considerable interest in K–12 engineering. The group has a large membership division devoted to K–12 engineering education issues, and the ASEE board of directors and Engineering Deans Council both have committees that focus on K–12 engineering education. ASEE is also the source of much of the published research on K–12 engineering education in the United States, primarily through annual conference proceedings papers and its peer-reviewed *Journal of Engineering Education*, which focuses on both K–12 and higher engineering education.

The impact of ASEE's organizational and publishing activities in K–12 engineering has not been measured, and it would be difficult to do so. Nevertheless, it seems clear the society's efforts and the combined influence of its many engineering educator members have stimulated the development of K–12 engineering education in the United States.

CONCLUSION

We have highlighted elements of the system that supports K–12 teachers as they develop the capacity to teach engineering. Although the system is far more complex and includes other stakeholders and components, we have described elements and interactions with great current and potential future impact on that capacity. However, there are opportunities to improve the system's support of teachers and to improve teaching and learning of engineering at the K–12 level.

For example, ESSA provides openings for states to support K–12 engineering teacher preparation and leadership development, but because states are not required to spend their federal money in these areas, it is not clear that any spending actually has occurred or will in the future. The same is true regarding the ESSA-required science assessments. The law allows but does not require that states develop assessments that include engineering concepts and practices.

As noted, research is needed to move the field forward. Such research can both be conducted by researchers who specialize in K–12 engineering education research, as well as collaborations

[24] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=500047
[25] https://engineering.purdue.edu/INSPIRE

that involve interdisciplinary teams of scholars and practitioners. Design-based research (DBR) and design-based implementation research (DBIR) methodologies (Kelly et al. 2008; see http://learndbir.org), which are used for studying complex problem-solving with multiple stakeholders, are highly iterative, nimble, and adaptive, and may be particularly useful. In DBIR, practitioner teachers and researchers, along with other stakeholders (e.g., students, administrators), consider problems from multiple angles but in all cases the teachers help define them. The process focuses on building theory and practical capacity to support program enactment and improved student learning outcomes (LeMahieu et al. 2017b). Teacher Design Research (Bannan-Ritland 2008), which employs a teacher-as-researcher model and investigates complex instructional tasks such as teaching with engineering design activities, might also be relevant.

However, merely building research infrastructure will not necessarily lead to improved teacher development. For research to improve professional learning experiences and materials, results must be translated into practical guidance and disseminated to the community. A research-to-practice cycle, in which researchers and practitioners collaborate to define and answer research questions that are translated into tools that improve educational practice, can yield both evidence-based change and more research questions to drive further improvements. This interaction of innovation and research on teaching and learning can improve efforts to develop more engaging learning environments and a more inclusive and welcoming environment for all students (ASEE 2009).

Similarly, networked improvement communities (NICs; LeMahieu et al. 2017a) merge the concepts of "networked science," which applies the shared knowledge of a group to solve multifaceted problems, and "improvement science" that formalizes continuous and iterative improvements in an organization or system (p. 6). In a NIC, individuals learn and reflect on information or behaviors and share that knowledge with others in their own organization. The larger network of organizations then learns and improves from gains at the individual and organization levels (LeMahieu et al. 2017a).

In the context of preparing K–12 teachers to teach engineering, individuals may be teachers, teacher leaders, principals, teacher educators, and engineering education researchers, among others. At the organizational level, the teachers, teacher educators, and principals form a school organization, while the teacher educators and engineering education researchers might work together at higher education institution. In a NIC, these organizations would work together and communicate with others in their district or state to share promising practices. However, all components of the system this change must develop an institutional culture that supports change.

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Conclusions and Recommendations

This report details changes in the US education system that are intended to integrate engineering in the K–12 curriculum, and it considers the implications of those changes for the teacher workforce. Although it is not possible to say with certainty how many elementary and secondary teachers currently are providing their students with experience and engagement with engineering concepts and practices, moving forward it seems highly likely that more K–12 educators will need some level of engineering literacy and engineering-related pedagogical knowledge. In addition, the different goals for K–12 engineering education suggest different levels and types of preparation for many K–12 teachers of engineering. (As a reminder, the committee is using the term "teacher of engineering" to refer to any elementary or subject-matter secondary teacher who spends some portion of the school day providing engineering instruction.)

The engineering education research field has established, high-level standards for programs that provide professional development for K–12 teachers of engineering. Beyond this general guidance, however, we know little about the factors most likely to lead to the effective preparation of such teachers. In addition, there are relatively few opportunities, especially at the preservice level, for K–12 educators to develop the knowledge and skills needed to teach engineering, which raises questions about the capacity of the US education system to meet the potential demand for K–12 teachers of engineering. Furthermore, there is a lack of research on the impacts of different kinds of preparation for K–12 teachers of engineering, in terms of student outcomes, to gauge the effectiveness and merits of various approaches and programs. Addressing the capacity concern, in turn, highlights the roles and importance of elements of the larger education system.

This chapter presents the committee's conclusions and recommendations and is based on the data and analysis in the rest of the report. The chapter is intentionally brief, discussing only the most critical issues and opportunities. The order of its four sections, which address context, preparation, systems factors, and research, is not intended to suggest prioritization of any suggestions over others. Every recommendation calls for action by one or more stakeholders, all of whom have roles to play in helping strengthen the preparation of K–12 teachers of engineering.

CONTEXT FOR THE PREPARATION OF K–12 TEACHERS OF ENGINEERING

Many factors are contributing to an expanded focus on engineering in K–12 STEM education in the United States. These include widespread calls for a STEM-literate workforce; concerns about the country's international competitiveness; the growing presence of K–12 STEM curricula that incorporate engineering concepts and practices; and the availability and adoption by states of K–12 standards with engineering learning goals for students.

CONCLUSION: Current circumstances provide incentives and opportunities to increase both the number and competence of K–12 teachers of engineering in the United States. The incentives and opportunities arise not only from a generally favorable policy environment, including widely adopted engineering-containing standards, but also from the potential availability of new, rewarding career options for individuals able to teach engineering at the K–12 level.

Federal efforts to determine the size of the workforce of K–12 teachers of engineering are hindered by shortcomings in a key survey instrument, the National Teacher and Principal Survey (NTPS). As discussed in chapter 4, one of three engineering-related "main teaching assignments" in the survey ("Construction trades, engineering, or science technologies [including computer-aided design and drafting]") includes engineering but also other subjects, which could result in an overestimate of the size of the workforce. At the same time, other aspects of the survey might lead to an underestimate of the workforce. For instance, because the instrument discourages educators from selecting subjects that are not their main assignment, those who teach one or more engineering classes but whose main assignment is in a different subject may not consider themselves to be teachers of engineering. The survey is also unlikely to count secondary science teachers who are introducing their students to engineering design projects in keeping with the *Framework for K–12 Science Education* and *Next Generation Science Standards*, as well as elementary teachers who tend to be subject-matter generalists. Given the nascent state of K–12 engineering education in the United States, the vast majority of teachers of engineering are likely to be teaching engineering less than full-time. This population likely is not captured by NTPS, so the survey data may reflect a significant underestimate of K–12 educators teaching at least some engineering.

CONCLUSION: Limitations in available data and definitional confusion about what constitutes a K–12 teacher of engineering make it difficult to estimate how many such individuals are currently working in the United States.

RECOMMENDATION 1: To better understand the extent to which US K–12 educators are teaching engineering, the National Center for Education Statistics should revise the National Teacher and Principal Survey so that (1) answer choices for items that query respondents about teaching assignments and certification do not combine engineering with other fields, and (2) respondents can indicate whether they are engaged in teaching engineering less than full-time or as other than a main teaching assignment (e.g., as part of a science course).

Data reviewed by the committee suggest that there are very few preservice programs preparing K–12 teachers of engineering (or science educators who are knowledgeable enough about engineering to successfully introduce it to their students). As spelled out in chapter 4, one source of teachers of engineering is the teacher preparation programs in technology education. However, not all of these programs engage their students in engineering coursework, and the number of graduates is small and has been declining for at least the last two decades. Other preservice programs, such as the UTeach initiative, produce a very small number of graduates with engineering degrees, and nearly all of those graduates end up teaching science or mathematics, not engineering. The committee could find no reliable information about the extent to which science teacher education programs engage their students in engineering content, practices, and pedagogy. Based on our own expertise and knowledge in this area, however, we conclude that very few such programs incorporate engineering in a meaningful way.

CONCLUSION: Despite the challenges associated with determining the size of the K–12 engineering educator workforce, evidence points to a likely current and growing mismatch between the need for engineering-literate K–12 educators and the capacity of the US education system to prepare and support these professionals.

RECOMMENDATON 2: To begin to address the systemic lack of capacity to prepare preservice K–12 teachers of engineering, federal agencies, such as the Department of Education and National Science Foundation, and private foundations with an interest in STEM education, should convene a collaborative dialogue among K–12 STEM educators, leaders at organizations involved in the preparation of K–12 STEM educators, colleges of education, colleges of engineering and engineering technology, postsecondary science departments, K–12 teacher accrediting bodies, state departments of education, and technology-focused industry. The goal should be to identify practicable steps that the stakeholders and others can take to address the capacity issue.

CONCLUSION: Independent of the overall number of educators, federal and other data suggest that the current composition of the current K–12 engineering educator workforce is heavily weighted toward white males. This pattern mirrors longstanding gender and racial imbalances in the field of technology education, currently one of the main sources of new K–12 teachers of engineering, as well as in postsecondary engineering and engineering technology education. A more diverse workforce of K–12 teachers of engineering that is encouraged to use inclusive pedagogies could help attract and retain a more diverse population of students interested in the study of engineering and in STEM-related careers.

RECOMMENDATION 3: Programs that prepare prospective teachers of engineering need to make greater efforts to recruit and retain teacher candidates from populations currently underrepresented in STEM education and careers. Likewise, professional development programs should proactively encourage the participation of teachers with these characteristics. Programs for both prospective and practicing teachers should explicitly include instruction on the use of inclusive pedagogies.

PREPARING K–12 TEACHERS OF ENGINEERING

The goals of K–12 engineering education vary, and this variation has implications for the preparation of educators. A basic understanding of engineering—engineering literacy—is important for all K–12 teachers of engineering and should include both subject-matter knowledge as well as engineering-specific pedagogical content knowledge. A subset of K–12 teachers of engineering will need to have greater familiarity with engineering concepts and practices as well as more extensive knowledge of relevant science and mathematics in order to serve students who require deeper learning experiences in engineering in order to pursue certain college or career goals.

CONCLUSION: Educators aiming to support student acquisition of engineering literacy do not need to have a degree in engineering. However, current and prospective K–12 teachers of engineering do need appropriate levels of experience and engagement with engineering concepts, practices, and pedagogy. The amount of experience and engagement will vary according to grade band, with teachers at the secondary level generally requiring more than those working in elementary classrooms.

CONCLUSION: K–12 teachers of engineering should be able to support students in the acquisition of important engineering concepts, skills, and habits of mind. The *Standards for Preparation and Professional Development for Teachers of Engineering* provide a useful starting point for meeting the professional learning needs of these educators. State standards for teacher education and for assessment related to certification, some of which are discussed in chapter 5, may provide additional guidance to those involved in the preparation of K–12 teachers of engineering.

RECOMMENDATION 4: In the short term, both providers of professional development opportunities and educators of prospective K–12 teachers of engineering should align their work with guidance documents that draw on the most up to date understanding of research and best practices in teacher education and professional development. As new knowledge accumulates about the professional learning of K–12 teachers of engineering, adjustments in programs should reflect new insights gained from rigorous, high quality scholarship.

RECOMMENDATION 5: As evidence accumulates about effective approaches for preparing K–12 teachers of engineering, it will be important to establish formal accreditation guidelines for K–12 engineering educator preparation programs, such as those developed by the Council for the Accreditation of Educator Preparation. The National Science Teaching Association, International Technology and Engineering Educators Association, and American Society for Engineering Education should work together to determine the appropriate content for such guidelines. Such an effort should take account of new NGSS-aligned accreditation standards for science teacher education programs, which become effective in 2020 and include student learning expectations related to engineering. It should also consider how the guidance needs to vary based on the grade level to be taught.

CONCLUSION: The inclusion of engineering-related learning expectations for students in the *Framework for K–12 Science Education* and NGSS will require a considerable shift in science teachers' instructional practices. Successful implementation of these changes will require significant support for science teachers' professional learning and sufficient time and resources for multiple cycles of iteration, reflection, and improvement.

RECOMMENDATION 6: Programs that prepare preservice K–12 science educators or provide professional learning to in-service science teachers need to address the call in the *Framework* and NGSS for students to connect their science learning to engineering ideas and practices. To this end, the Association for Science Teacher Education, National Science Teaching Association, and American Society for Engineering

Education should work together to assist these programs in identifying and implementing actions that will fulfill the engineering components of the new vision for K–12 science education.

KEY INFLUENCES ON THE SYSTEM

Increasing the number, skill level, and confidence of K–12 teachers of engineering in the United States is a complex challenge that will require attending to multiple elements of the education system. Two components of the system are of special significance in the context of teacher professional learning: postsecondary institutions and state departments of education. Given the extent of the changes required, the need to coordinate across multiple components of the education system, and that system's current limited capacity to prepare K–12 teachers of engineering, meaningful improvements in the availability and quality of teacher learning opportunities should be expected to occur incrementally over many years, a decade or more.

CONCLUSION: Postsecondary engineering and engineering technology programs are a potentially important but underutilized resource for helping build a sufficiently large and competent workforce of K–12 teachers of engineering. These institutions could provide K–12 educators with the disciplinary expertise and habits of mind that they will need to be effective instructors and role models to K–12 students. One potential starting point might be the small group of universities that have established schools or departments of engineering education. Some of these programs already conduct research on K–12 engineering education, and many graduate PhD students with deep knowledge of effective pedagogy. The engineering schools that have agreed in principle to provide credit for a high-school engineering course may also have motivation to help prepare K–12 teachers of engineering. Because few engineering or ET programs have expertise in K–12 pedagogy, it will be important that these institutions engage colleges of education or other sources of pedagogical expertise in their efforts.

RECOMMENDATION 7: Postsecondary engineering and engineering technology programs should partner with schools/colleges of education to design and implement curriculum for the preparation of K–12 teachers of engineering. Such efforts should be conducted in consultation with teacher professional organizations that have a stake in K–12 engineering, such as the International Technology and Engineering Educators Association and National Science Teaching Association, as well as the American Society for Engineering Education.

CONCLUSION: The committee's research revealed considerable variability in the types of engineering-related credentialing states offer. There is also variation within and across states regarding (1) what knowledge and skills teachers in these fields must master to be credentialed, (2) to what degree work experience may substitute for academic coursework, and (3) what subjects those with credentials can teach.

RECOMMENDATION 8: States should work together to reach high-level agreement about what constitutes appropriate preparation and credentialing for teachers of engineering at various grade levels and what education and work-related pathways

satisfy the credential process. The Council of Chief State School Officers should organize such discussions, in consultation with appropriate science and engineering professional societies and test development organizations.

CONCLUSION: Many types of organizations with a stake in the US education system provide expertise, funding, and other supports to improve the accessibility and quality of K–12 STEM education. It is not always clear, however, that these well-intentioned efforts are informed by evidence from research or the wisdom of practice, or that these organizations are effectively leveraging the potential for partnership with the entities they are trying to assist.

RECOMMENDATION 9: Federal agencies, higher education institutions, state education agencies, industry, informal learning institutions, cultural and community organizations, and other stakeholders in the preparation of K–12 teachers of engineering should work in partnership with the schools and educators targeted by the interventions. When possible, such partnerships should leverage the expertise of teacher leaders in K–12 engineering education. Investments by these stakeholders should be allocated and used in ways that are consistent with findings from education, social science, and learning sciences research as well as relevant policy documents.

DIRECTIONS FOR RESEARCH

As this report makes abundantly clear, the evidence base that might inform effective approaches to preparing K–12 teachers of engineering is thin and uneven. This situation is due to the relative newness of engineering education in the K–12 landscape as well as the challenges inherent to conducting high-quality research in education. The committee was struck by the fact that the promising expansion of engineering instruction across the K–12 grades presents a significant opportunity to learn from the experiences of those who designed these initiatives as well as the teachers spearheading them. Research we describe, for example, demonstrates clearly that teachers learn a great deal about student ideas and the potential of various instructional approaches and materials as they experiment with implementing engineering in their classrooms.

CONCLUSION: Given the nascent nature of K–12 engineering education and the relatively small amount of active research on teacher professional learning in this domain, the use of designed-based research methods may be particularly appropriate. Design-based research (DBR) and design-based implementation research (DBIR) methods, which are used for studying complex problem solving with multiple stakeholders, are highly iterative, nimble, and adaptive. Teacher design research, which employs a teacher-as-researcher model and investigates complex instructional tasks, such as teaching with engineering design activities, might also be a useful approach.

CONCLUSION: There is no shortage of important issues that researchers in education and the social sciences might tackle. If anything, the challenge will be to decide where to focus attention and resources in order to have the greatest impact on the capabilities of K–12 teachers of engineering.

RECOMMENDATION 10: Federal agencies, such as the National Science Foundation and Department of Education, with a role in supporting K–12 STEM education, should fund research on topics relevant to the professional development of practicing and the education of prospective K–12 teachers of engineering. To the extent practicable, the efforts should take advantage of methods, such as design research, that encourage collaboration with stakeholders and existing reform efforts.

Pressing issues include:

- **Describe the subject-matter content knowledge and pedagogical content knowledge required for high-quality K–12 engineering education and how this knowledge varies across grade levels;**
- **Describe pedagogical approaches and specific instructional practices that effectively support students' integration of engineering with concepts and practices from the other STEM subjects;**
- **Document student learning progressions, age-appropriate expectations for engineering design thinking, and student conceptions in engineering, all of which have implications for how K–12 educators at different grade levels are prepared and supported; and**
- **Develop valid measures of teacher knowledge and instruction, as well as of student outcomes, that can be used to judge the effects of K–12 engineering educator preparation and professional learning programs.**
- **Characterize the current cadre of educators of K–12 teachers of engineering and their learning needs.**

FINAL THOUGHTS

The statement of task charged the committee with examining issues related to the preparation of K–12 teachers of engineering, a new, evolving, and important segment of the US STEM education workforce. As we hope this report makes clear, there is considerable potential value in engaging K–12 students in the concepts, practices, and habits of mind of engineering. Ideally, teachers who provide that engagement, whether from a foundation of engineering, technology education, science, or some other subject, should be engineering literate. They should also have the pedagogical content knowledge to guide students through the challenges and rewards of using the engineering design process and in the appropriate application of concepts and practices from science and mathematics. Findings from high-quality research in education should inform the professional learning of these educators.

For reasons both historical and structural, the current situation is far from this ideal. As our report points out, there are almost no postsecondary programs educating prospective K–12 teachers of engineering, and state mechanisms for recognizing prospective teachers' engineering knowledge, where they exist, vary widely. There are a number of K–12 engineering professional learning initiatives in the United States, some of which have reached considerable scale. Most of these efforts are small, however, and not grounded in evidence from research. In short, there are few professional pathways for those hoping to become K–12 teachers of engineering.

If this report can do one thing, we hope it will be to alert constituencies with a stake in US STEM education to the mismatch between the need for engineering-literate K–12 teachers and the education system's lack of capacity to meet this need. The situation is far from hopeless, but meaningful improvement will require action on multiple fronts, as this chapter proposes. The potential benefits for students and the nation are significant.

Appendix A: Committee Biographies

Ellen Kullman (NAE), Chair, is CEO and president of Carbon and retired CEO and chair of DuPont. She is on the boards of Goldman Sachs and Amgen. A native of Wilmington, Delaware, Mrs. Kullman holds a B.S. in mechanical engineering from Tufts University and an M.S. in Management from Kellogg School of Management of Northwestern University. She began her 27-year career at DuPont in 1988. Prior to joining DuPont, she worked for Westinghouse and General Electric. Mrs. Kullman was named CEO at the beginning of 2009 and board chair late that year, becoming the 19th executive to lead DuPont since its founding in 1802. Prior to those appointments she served as president, executive vice president and a member of the company's office of the chief executive. As a business leader, she led double-digit growth of the company's Safety & Protection business portfolio, started-up two successful high-growth businesses known today as DuPont Industrial Biosciences and DuPont Sustainable Solutions. During her seven years as CEO, Mrs. Kullman led the company's focus on growth in emerging international markets and championed the power of DuPont science and global market knowledge to transform industries. She decisively positioned the company for its next generation of growth, executing a strong plan that is delivering results today while positioning DuPont for future growth. She is a board director of United Technologies Corp, Carbon and Dell Technologies. She is a member of the National Academy of Engineering and past president of the U.S. China Business Council. She serves on the board of trustees of Northwestern University. Mrs. Kullman has been named as one of the "50 Most Powerful Women in Business" by Fortune and one of the "World's Most Powerful Women" by Forbes. She has received honorary doctorates from Lehigh University, the University of Edinburgh and the University of Delaware.

Diran Apelian (NAE) is Distinguished Professor of Materials Science at the University of California, Irvine and serves as Chief Strategy Officer for the Samueli School of Engineering. He is on leave from WPI, where he has been the Alcoa-Howmet Professor of Engineering and Founding Director of the Metal Processing Institute (MPI). He received his B.S. degree in metallurgical engineering from Drexel University in 1968 and his doctorate in materials science and engineering from MIT in 1972. He worked at Bethlehem Steel's Homer Research Laboratories before joining Drexel University's faculty in 1976. At Drexel he held various positions, including professor, head of the Department of Materials Engineering, associate dean of the College of Engineering and vice-provost of the University. He joined WPI in July 1990 as WPI's Provost. In 1996 he returned to the faculty and led the activities of the Metal Processing Institute, which he founded. He is credited with pioneering work in various areas of solidification processing and powder metallurgy – specifically in molten metal processing, aluminum alloy development, plasma deposition, spray casting/forming, and semi-solid processing of metals. During the last decade, he has worked on sustainable development issues, and particularly, resource recovery, reuse, and recycling. Apelian is the recipient of many distinguished honors and awards – national and international; he has over 700 publications to his credit; and serves on several technical, corporate and editorial boards. During 2008/2009, he served as President of TMS. Apelian is a Fellow of TMS, ASM, and APMI; he is a member of the National Academy of Engineering (NAE), National Academy of Inventors (NAI), European Academy of Sciences, and the Armenian Academy of Sciences. The 2016 Bernard Gordon Prize for Innovation in

Engineering Education was awarded to WPI – and the four recipients were: Diran Apelian, Kris Wobbe, Art Heinricher and Rick Vaz.

Rodger Bybee was Chair of the OECD's Science Forum and Science Expert Group and was a Questionnaire Panel Consultant for Program for International Student Assessment (PISA) 2006. Until 2007, Dr. Bybee was Executive Director of the Biological Sciences Curriculum Study (BSCS), a non-profit organization in Colorado Springs, Colorado that develops curriculum materials, provides professional development for the science education community, and conducts research and evaluation on curriculum reform. Prior to joining BSCS, he was Executive Director of the National Research Council's (NRC) Center for Science, Mathematics, and Engineering Education (CSMEE), in Washington, D.C. Between 1985 and 1995, he participated in the development of the National Science Education Standards, and between1992–1995 he also chaired the content working group of that NRC project. At BSCS, Dr. Bybee was the principal investigator for four National Science Foundation (NSF) programs. His work at BSCS also included serving as Principal Investigator for programs to develop curriculum frameworks for teaching about the history and nature of science and technology for biology education at high schools, community colleges, and four-year colleges. From 1972 to 1985, Dr. Bybee was Professor of Education at Carleton College in Northfield, Minnesota. He has been active in education for more than forty years, having taught science at the elementary, secondary, and college levels. Dr. Bybee serves on a number of advisory boards and committees including those for the National Academies, The U.S. Department of Education, The National Science Foundation, and The American Institute of Biological Sciences. He previously chaired the National Forum for the Organization of Economic Cooperation and Development (OECD) for the 2006 PISA in Science. In addition, he is an advisor to the Trends in Mathematics and Science Study (TIMSS) video projects. Dr. Bybee has written widely, publishing in both education and psychology. He is co-author of a leading textbook titled Teaching Secondary School Science: Strategies for Developing Scientific Literacy. His recent books address STEM (Science Technology Engineering and Mathematics) education. Over the years, Dr. Bybee has received many accolades as an educator and leader in science education. In 1979 he was Outstanding Science Educator of the Year. In 1989 he was recognized as one of the 100 outstanding alumni in the history of the University of Northern Colorado. In 1998, he was presented with the Distinguished Service to Science Education Award by the National Science Teachers Association (NSTA). In 2001, he received the first American Institute of Biological Sciences Education Award. In 2007, he received the Robert H. Carleton Award, NSTA's highest honor for national leadership in science education.

Jason Coleman is the Co-Founder and Executive Director of Project SYNCERE, an educational not-for-profit organization dedicated to exposing and preparing under-served students for careers in the STEM (Science, Math, Engineering and Technology) fields. After graduating from the University of Southern California with a degree in Mechanical Engineering, he worked in the aerospace industry for 3 years at BAE SYSTEMS, where he designed and developed flight control systems for military and commercial aircrafts. He was later employed with Motorola Mobility for 5 years, where he developed the mechanical layouts for the latest cellular phones. During his tenure in corporate America, he noticed the dismal amount of minorities and women in the fields of engineering and decided a change was necessary. In 2008, he co-founded Project SYNCERE in an effort to bring about a change within the STEM fields. As a product of the

Chicago Public School system (Whitney Young), it was important for the co-founder to ensure access to quality programs was available to inner city youth. Project SYNCERE has since served over 10,000 Chicago area students since their launch, helping to increase their interest in STEM and improve their overall understanding of engineering. Project SYNCERE has been recognized for its' outstanding work and dedication to youth in the community by organizations such as the Urban League of Chicago, NBCUniversal, N'Digo, Diversity in Action, Black Enterprise and the Chicago Sun-Times. Project SYNCERE is now in its 8th year of operation and has been able to have an incredible impact on the youth throughout Chicago. Through our partnerships with schools, universities and other community organizations we have been able to serve more than 10,000 youth since its inception. Project SYNCERE currently provides programming in more than 30 schools throughout Chicago as well as operates a year-round engineering academy to provide students with a pathway to engineering success. Our out-of-school time programs have seen great success over the years. We have been able to graduate 100% of our high school seniors, with 86% of them going on to college to major in a STEM related field. Of those students studying STEM at the post-secondary level 90% have chosen to major in engineering. Our goal is to create a national organization that will reshape the way engineering is accessed and taught to students throughout the nation. We want to ensure that all students are provided an opportunity to develop 21st century technological skills, which will be necessary to drive our country forward as a world leader in innovation. In his spare time, Jason volunteers with other local non-profits and sits on the Advisory Board for the Chicago Children's Museum. Jason has been the recipient of numerous awards for his efforts in the community and has spoken on numerous panels about Strategies and Equity in STEM Education.

David Crismond serves as the Program Director of Childhood Education and is an Associate Professor at the City College of New York's School of Education, and has a courtesy appointment with the Grove School of Engineering. After 11 years as a classroom teacher, he earned a MS from MIT's ME department, and an Ed.D from Harvard's Graduate School of Education. With the support of NSF funding, he created design-based science curriculum at TERC and Georgia Tech, as well as-video-based teacher professional development materials for the website, *Design in the Classroom*. At CCNY, he teaches elementary science and engineering methods courses for pre- and in-service teachers, and an inquiry and writing seminar for freshmen where students use design thinking to plan their college and vocational careers. His research interests involve K-16 integrated STEM learning and teaching, with a focus on the use of science and math concepts in the context of doing hands-on technology investigations and engineering design tasks. He and colleagues have developed a framework that describes key dimensions of teachers' design pedagogical content knowledge, and guidelines for science and technology education teachers to create video-based teaching portfolios when using engineering activities in the classroom.

Marshall (Marty) Davis graduated from the University of Minnesota in 1984 and started his career in education teaching 6th–8th grade science at a private school in St. Paul. In 1988, Marty accepted a position as a 5th grade teacher in the Omaha Public Schools, and while in Omaha earned a Masters in Administration from the University of Nebraska at Omaha. He moved back to St. Paul in 1992 to become the elementary science specialist at Hancock Hamline University Collaborative Magnet. While at Hancock, he served on a number of district and state science committees and was awarded the Presidential Award for Excellence in Math and Science in

2000. Marty became a district science coach in 2002 and has coached science teachers at the elementary, middle school and high school level. Currently, he is the Supervisor of K–12 Science for Saint Paul Public Schools, focusing on K–12 science and engineering curriculum, teacher professional development, and community partnerships. He is a Co-PI on an $8,000,000 NSF grant focused on ways to truly incorporate all aspects of STEM within a single scenario based unit. Marty is also a Co-PI on a Math Science Partnership grant with BSCS and the University of Minnesota STEM Center. Marty has served on a number of NSTA science conference committees, facilitated the creation and adoption of the 2003 and 2009 Minnesota Academic Science Standards, which included engineering standards as part of science, and was a state lead for the Next Generation Science Standards Review. He is often a guest lecturer at local colleges and regularly teaches elementary science methods courses for pre-service teachers at the University of Minnesota. He has served on a number of science and STEM committees and boards and is currently ending a six-year term on the Executive Board of SciMathMN, a non-partisan business/K-16 coalition that promotes STEM in Minnesota.

Cheryl Farmer is Director of Precollege Engineering Education Initiatives at The University of Texas at Austin (UT Austin), where her work focuses on creating and facilitating multidisciplinary collaborations to develop standards-based, research-based engineering curricula and instructional support programs. As co-founder of the National Science Foundation-funded UTeachEngineering program, she led UT Austin’s efforts to develop and roll out a high-quality, low-cost, hands-on, project-based high school engineering course; an innovative teacher professional development and induction program; and undergraduate and graduate degree programs for pre-service and in-service teachers of engineering. In 2012, recognizing the need for clear guidance to assist K-12 teachers and administrators in selecting appropriate professional development opportunities for engineering, she launched a national effort to develop a research-based framework of Standards for Professional Development for K-12 Teachers of Engineering. Her previous work in higher education includes the creation of an academic enrichment and mentorship program for university freshmen with a special focus on supporting first-generation college students. Ms. Farmer is a past recipient of the Dodd Teaching Excellence Award from the Department of Mathematics at The University of Texas at Austin.

Jen Gutierrez began her education career in Arizona in 1988 teaching 1st–4th grades, including K–2 multi-age classes. In 2006 she moved into the role of Science Curriculum Specialist at the district level, coaching K-12 teachers, providing support in science instruction, and coordinating the district-wide science and engineering fair. After a year at Arizona Science Center Jen joined the Arizona Department of Education in 2014 as the K-12 STEM Education Specialist in the Standards Division. Jen "retired" in 2017 and is currently working as a K-12 STEM Education consultant. She is a proud member of the NGSS writing team, including the Diversity and Equity team, and is an endorsed trainer for the Museum of Science, Boston’s Engineering is Elementary (EiE) program working with teachers around the U.S. Jen stays actively engaged in science education at the state and national level, currently serving as Division Director of Professional Learning in Science Education on the National Science Teaching Association’s board. She earned a BS in Journalism and a post-degree K-8 Certificate from Northern Arizona University, received her master’s in Elementary Education from Arizona State University, and an Administration Certification from NAU.

Tanner Huffman is an assistant professor in the Department of Integrative STEM Education, School of Engineering at The College of New Jersey, and Executive Director of the Advancing Excellence in P-12 Engineering Education Research Collaborative (AE3). Before joining the faculty at TCNJ, Dr. Huffman was the Director of Research, Assessment and Special Projects at the International Technology and Engineering Educators Association (ITEEA). While at ITEEA, he secured funding from the National Science Foundation, the Kuwait Foundation for the Advancement of Sciences, the Utah governor's office of economic development, and several other private foundations with the goal to provide high quality STEM curriculum and professional development to all students. Dr. Huffman continues to serve ITEEA as a senior advisor and consultant. He is a strong advocate for K-12 Engineering Education with experience as a middle and high school Engineering and Technology Education teacher and a focus on social relevance and empowerment. Dr. Huffman has published in international journals and presented at regional, state, national and international conferences. Dr. Huffman has also served as a board member of the American Society of Engineering Education's Precollege Engineering Education Division; as an advisor for Carnegie Mellon University's CREATE Lab Satellite Network; and the national event coordinator for the Test for Engineering Aptitude, Math, and Science (TEAMS) student competition.

Bryan Kind is Vice President of Programs at Project Lead the Way (PLTW). In this role, he leads the PLTW Professional Development program, which supports over 75,000 Computer Science, Biomedical Science, and Engineering pk-12 teachers across America, as well as the PLTW Production Team that is responsible for creating dynamic student and teacher learning experiences. He is passionate about driving innovation and quality to produce inspiring and transformative learning experiences for pK-12 students and teachers. Prior to his current role within PLTW, Kind served as Senior Director of Programs, Director of Professional Development, Director of eLearning, and Associate Director of Curriculum for Engineering. Prior to joining PLTW, Kind was a technology and engineering teacher in the Milwaukee, Wisconsin, metro area. He also served as a PLTW Principles of Engineering Master Teacher and delivered teacher training experience across the country. Kind holds a Master of Science in Education Administration and Supervision from Concordia University Wisconsin and a Bachelor of Science in Technology Education from the University of Wisconsin – Stout.

Chentel Neat currently works at Colbert Museum Magnet school as the STEM magnet coordinator has been a teacher with Broward County Public Schools for the past 8 years. She holds a Bachelor of Science in Early Childhood Education from Florida International University and is also ESOL and Gifted endorsed. She has taught both 1st and 2nd grades and currently works at Colbert Elementary Museum Magnet school as the 2nd grade gifted/high achievers teacher. Colbert's magnet program is focused on STEM; a portion of the curriculum focuses heavily on these areas and the school utilizes various programs and curricula to enhance the STEM Museum component of the magnet program. Colbert currently uses the Engineering is Elementary curriculum to address the "E" in STEM. In 2013, Neat was recorded by the Museum of Science, Boston teaching one of the units. These recordings were developed into Classroom Videos for the EiE website and serve to support teachers as they use the curriculum. Neat has also been awarded a scholarship from EiE that provides the opportunity to train to become a professional development provider of their curriculum.

Brian J. Reiser is professor of learning sciences at Northwestern University. Dr. Reiser's research examines how to make the scientific practices of argumentation, explanation, and modeling meaningful and effective for classroom teachers and students. Reiser co-led the development of IQWST (Investigating and Questioning our World through Science and Technology), a three-year middle school curriculum that supports students in science practices to develop disciplinary core ideas. Reiser is a member of the National Research Council's Board on Science Education. He has served on the NRC committees authoring the reports A Framework for K-12 Science Education (which guided the development of the Next Generation Science Standards), Developing Assessments for the Next Generation Science Standards, and Guide to Implementing the Next Generation Science Standards. Dr. Reiser has also worked with Achieve on tools to support implementation of NGSS. Dr. Reiser is currently collaborating with several state initiatives to design and provide professional development and to develop curriculum materials for K-12 teachers to support them in realizing the reforms in NGSS in their classrooms. Dr. Reiser earned his Ph.D. in cognitive science from Yale University.

Maria C. Simani is the Executive Director of the California Science Project (CSP), a statewide network providing professional development for K-12 teachers in science. A physicist, Dr. Simani received her Ph.D. in experimental particle physics in the Netherlands and then conducted particle physicist research at DESY, Germany, at the Stanford Linear Accelerator Center, and at the Lawrence Livermore National Laboratory. Dr. Simani also performed research on brain functioning and learning at the Keck Institute for Integrative Neuroscience at the University of California, San Francisco. Since 2012, Dr. Simani has served on the Science Expert Committee of the California Department of Education to review and provide recommendations for the adoption and implementation of the Next Generation Science Standards. Dr. Simani and the California Science Project have also contributed as lead writers of the new California Science Curriculum Framework. Dr. Simani served as member of the K-12 education subcommittee at the American Physical Society. The California Commission on the Status of Women and Girls nominated Dr. Simani in 2013 as one of the Trailblazer STEM Women of the Year, and the California Science Teachers Association recognized Dr. Simani for her distinguished service to science education in California in 2016 and 2019.

Blaire Thrasher is an Engineering and Technology Education Instructor at East Coweta Middle School in Senoia, Georgia. A middle school teacher for thirteen years, she sponsors the First Lego League team and two Technology Student Association chapters at the middle school and high school levels in her county. Blaire earned an undergraduate degree from Georgia Southern University in 2007, a master's degree from Valley City State University in 2010, and a specialist degree from Valdosta State University in 2012. She is a member of the International Technology and Engineering Educators Association (ITEEA), having served as state affiliate president, secretary, and reporter. In 2011, Blaire was named as Georgia's Teacher of Excellence at the ITEEA Conference. Her engineering and technology program was named an ITEEA Program of Excellence in 2012 and she was named an ITEEA Emerging Leader in 2013. Blaire serves as a National Teacher Effectiveness Coach and curriculum author for ITEEA's Engineering by Design. She served her State Department of Education as the coordinator for the Engineering and Technology Education Standards revision during the 2018-2019 school year.

Bruce Wellman is a National Board Certified Teacher (NBCT, Chemistry) who teaches chemistry and engineering design as part of the Olathe Engineering Academy at Olathe Northwest High School in Olathe, KS. Wellman completed his B.S. degree in general science (focus in chemistry) at Penn State University and his M.S. in Education at the University of Rochester (NY). He has taught overseas as an English teacher in French speaking Africa as well as a chemistry/AP Chemistry teacher in the United States in rural, urban, and suburban settings. He received the Presidential Award for Excellence in Science Teaching in 2009, served as a Teacher Ambassador Fellow at the U.S. Department of Education during the 2011-12 academic year and served as a National STEM Teacher Ambassador for the National Science Teachers Association (NSTA) & the National Council of Teachers of Mathematics (NCTM) during the 2017-18 academic year. Wellman was an inaugural member of the National STEM Education Advisory Panel which provides advice and recommendations to the U.S. Committee on Science, Technology, Engineering, and Mathematics Education (CoSTEM) for the federal government. Wellman has organized and lead small- and large-scale professional development for STEM teachers and has been active in bridging the gap between STEM Education research and classroom practices. He has provided workshops throughout the country on how to teach using a student-centered approach called Process Oriented Guided Inquiry Learning (POGIL) and was a contributing author for a published collection of high school chemistry POGIL classroom activities (POGIL Activities for High School Chemistry. Flinn Scientific, 2012). Wellman has presented and provided integrated-STEM teacher training internationally at the First Integrated STEM Leadership Summit in Asia (Cebu, Philippines, 2019). He has served on several NSF review panels and as co-author/co-Principal Investigator on the NSF DR K-12 funded project entitled, "Promoting Engineering Problem Framing Skill-Development in High School Science and Engineering Courses" (also known as "Building Informed Designers"). Wellman has also been involved with teacher preparation programs through serving as a mentor teacher for several chemistry student-teachers and teaching the Science Teaching Methods class for secondary pre-service teachers at Rockhurst University (Kansas City, MO). Wellman remains involved with pre-college engineering education at the national level and currently serves as a member of the American Society for Engineering Education (ASEE) Board of Directors' Committee on P-12 Engineering Education. Wellman has previously served on the executive board of the Pre-college Engineering Education (PCEE) Division of ASEE. At the state level, Wellman has been involved with Kansas' science standards development and teacher training through serving as the lead engineering standards reviewer for the Kansas' Lead State Review Team for the Next Generation Science Standards (NGSS).

Suzanne Wilson is a Neag Endowed Professor of Teacher Education at the University of Connecticut where she currently serves as Professor in the Department of Curriculum and Instruction. Her undergraduate degree is in history and American Studies from Brown University; she also has a M.S. in Statistics and a Ph.D. in Psychological Studies in Education from Stanford University. She was a University Distinguished Professor in the Department of Teacher Education at Michigan State University, where she served on the faculty for 26 years. Wilson also served as the first director of the Teacher Assessment Project (PI, Lee Shulman), which developed prototype assessments for the National Board for Professional Teaching Standards. Dr. Wilson is a committed teacher, having taught undergraduate, MA, and doctoral classes in educational policy, teacher learning, and research methods. She has directed 28 dissertations, and served as a committee member on another 35. While at Michigan State, Wilson collaborated on several large-scale research projects, including the National Center for Research on Teacher Education/Teacher Learning, the Educational Policy and Practice Study, and the National Partnership for Excellence and Accountability in Teaching. She has written on teacher knowledge, curriculum reform, educational policy, and teacher learning. She is currently co-PI on Learning science as inquiry with the Urban Advantage: Formal-informal collaborations to increase science literacy and student learning, a collaboration with Urban Advantage, a professional development program offered throughout NYC in which she is investigating what teachers learn from opportunities to engage in secondary science research. Her current work concerns exploring various measures of teaching and teachers' understanding that might be used for teacher education and education research, as well as a study of the contemporary and jurisdictional battles over who should control teacher education and licensure. She has published in American Educator, American Educational Research Journal, Educational Researcher, Elementary School Journal, Journal of Teacher Education, Phi Delta Kappan, and Teaching Education. She is author of California Dreaming: Reforming Mathematics Education (Yale, 2003), and editor of Lee Shulman's collection of essays, Wisdom of practice: Essays on teaching, learning, and learning to teach (Jossey-Bass, 2004). Wilson serves on multiple editorial and advisory boards; she is also a member of the National Research Council's Board on Science Education and the National Academy of Education.

Appendix B: Workshop 1 Agenda

Agenda

TUESDAY, April 18th: Keck 101

3:15	Setting the Stage: Guest Speaker *David Evans, National Science Teachers Association* • The political landscape for STEM education policy in the Trump era • Opportunities for engineering education related to the Every Student Succeeds Act • Opportunities for engineering education related to NGSS
4:00 – 5:30	Overarching Issues and Opportunities Facing US STEM Education: Implications for the Project *Moderator: Rodger Bybee, Biological Sciences Curriculum Study* *Equity/inclusion/diversity/English Language Learners* *Okhee Lee, Professor of Childhood Education, NYU* *STEM learning in children* *Douglas Clements, University of Denver* *Students with disabilities and STEM education* *James Basham, University of Kansas* *Rural and urban settings* *Matthew Irvin, University of South Carolina*
5:30	ADJOURN

WEDNESDAY, April 19th: Keck 100

7:30 am	Breakfast available
8:00 – 8:15 am	Welcome and Overview of Workshop Objectives *Ellen Kullman, Committee Chair*
8:15 – 9:30 am	Diverse Implementations of PreK-12 Engineering Education *Moderators: David Crismond, City College of New York, and Brian Reiser, Northwestern University* 1. *Christine Cunningham, Engineering is Elementary* 2. *Bryan Kind, PLTW* 3. *Bernie Zubrowski, EDC*
9:30 – 10:45 am	Pathways into PreK-12 Engineering: Educator Stories Part I *Moderator: Bruce Wellman, Olathe Public Schools Engineering Academy* • A career changer with an engineering/engineering technology degree

	Jose Rivas, Science Teacher, Lennox Math, Science and Technology Academy, Inglewood, CA • A middle school or high school science and engineering teacher *Amy Morriss, Academy of Our Lady, New Orleans, LA* • A middle school or high school math and engineering teacher *Brandon Hernandez, Engineering Academy, Olathe, KS* • A middle school or high school technology and engineering teacher *Glenn Bradbury, Bozeman High School, Bozeman, MT*
10:45 – 11:00 am	Break
11:00 am – 12:15 pm	Pathways into PreK-12 Engineering: Educator Stories Part II *Moderator: Chentel Neat, Colbert Elementary* • A middle school teacher *Julia Harth, HB Whitehorne Middle School, Verona, NJ* • An elementary teacher *Christopher Kohnke, Colbert Elementary, Broward County, FL* • Educators working in an informal setting (both museum/science center and in an after-school setting) *Adrianne Wheeler, Project SYNCERE, Chicago, IL* *Angie Brayford, SHINE, Shenandoah District, PA*
12:15 – 1:30 pm	Working Lunch (Table topics?) - Staff and Committee will have some topics for discussion and others would be gathered using the "parking lot" method.
1:30 – 2:30 pm	What works in educator professional development and what are common practices that don't? *Moderator: Suzanne Wilson, University of Connecticut* *Jim Short, Carnegie Corporation of NY* Respondent to look more specifically at engineering education: *Pam Lottero-Perdue, Towson University*
2:30 – 4:00 pm	Methods courses for science and engineering pre-service teachers: Similarities, differences, and implications *Moderator: David Crismond, City College of New York* Elementary Teacher Education *Pam Lottero-Perdue, Towson University*

	Karen Worth, Wheelock College Secondary Teacher Education *Robin Adams, Purdue University* *Ken Welty, University of Wisconsin-Stout*
4:00 – 5:30 pm	Breakout Sessions with Reporting Out (Topics/Questions Provided)
	ADJOURN

THURSDAY, April 20th: Keck 105

9:30 – 10:45 am	State Standards for Engineering and Technology Education: Implications for Preparation of PreK-12 Educators *Moderator: Jen Gutierrez, K-12 STEM Education Consultant* *Tanner Huffman, The College of New Jersey (TE standards)* *Tamara Moore, Purdue University (NGSS/Professional Development)* *Deidre Sessoms, Professor of Education, CSU Sacramento (NGSS, Pre-Service Education)*
10:45 – 11:30 am	Methods for demonstrating/determining K-12 educator competency to teach about engineering (to include formal and informal approaches to credentialing) *Moderator: Maria Simani, California Science Project* *Pat Yongpradit, Code.org (to describe challenges and issues in CS teacher credentialing)* *Michael De Miranda, Texas A&M University*

Appendix C: Workshop 2 Agenda

Wednesday, August 30

12:30 p.m. Lunch

1:00 p.m. LPI's report, *Effective Teacher Professional Development (2017)*: Implications for the project
(Background readings: (1) Effective Teacher Professional Development Factsheet; (2) Effective Teacher Professional Development Report)
Moderator: Bryan Kind, Project Lead the Way

Maria Hyler and Madelyn Gardner, Learning Policy Institute

- What findings from the report might apply to the preparation of K-12 teachers of engineering?
- What is the role of engineering design in pedagogy?
- What are the challenges and affordances of introducing math and science concepts through engineering design?

1:45 p.m. Evaluation data from PreK-12 Engineering PD programs
Moderator: Maria Simani, California Science Project

Beth Cady, NAE

- What data has been collected and what claims are made?
- What research questions should be addressed in future studies?

2:45 p.m. Credentialing of K12 Engineering Educators: Schools and Staffing Survey and a review of state policies
(Background readings: Kuehn SASS report; De Miranda report on credentialing)
Moderator: Bruce Wellman, Olathe Northwest High School, Olathe, Kansas

Greg Pearson, NAE: SASS
Michael De Miranda, Texas A&M: State policies (by WebEx)

- What do these data tell us about the prevalence of PreK-12 teachers assigned to teach engineering, with engineering certificates, or with engineering degrees?
- How do these data help address the relevant questions about professional pathways for educators, including those working in informal settings, in the SOT?
- What are the implications for the report?

3:30 pm *Break*

3:45 p.m. Connecting Engineering Skills/Dispositions to Workforce Needs
Moderator: Ellen Kullman, DuPont (ret.)

Jennifer Ryan Crozie, Vice President, IBM Corporate Citizenship,
President, IBM International Foundation
Maura Banta, Director of Citizenship Initiatives in Education, IBM

- IBM's experience with P-TECH schools
- Leveraging Watson to support teacher PD