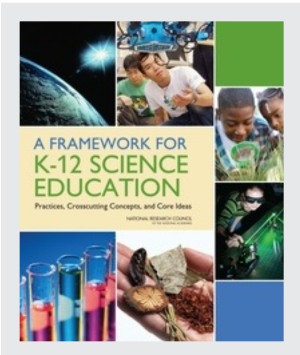
THE NATIONAL ACADEMIES PRESS

This PDF is available at http://nap.edu/13165

SHARE



A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas

DETAILS

400 pages | 8 1/4 x 10 | HARDBACK
ISBN 978-0-309-21441-4 | DOI 10.17226/13165

BUY THIS BOOK

FIND RELATED TITLES

AUTHORS

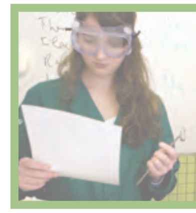
Helen Quinn, Heidi Schweingruber, and Thomas Keller, Editors; Committee on Conceptual Framework for the New K-12 Science Education Standards; National Research Council

Visit the National Academies Press at NAP.edu and login or register to get:

– Access to free PDF downloads of thousands of scientific reports
– 10% off the price of print titles
– Email or social media notifications of new titles related to your interests
– Special offers and discounts

Distribution, posting, or copying of this PDF is strictly prohibited without written permission of the National Academies Press. (Request Permission) Unless otherwise indicated, all materials in this PDF are copyrighted by the National Academy of Sciences.

Copyright © National Academy of Sciences. All rights reserved.



8

Dimension 3
DISCIPLINARY CORE IDEAS—ENGINEERING, TECHNOLOGY, AND APPLICATIONS OF SCIENCE

In Chapter 3, we assert that "any [science] education that focuses predominantly on the detailed products of scientific labor—the facts of science—without developing an understanding of how those facts were established or that ignores the many important applications of science in the world misrepresents science and marginalizes the importance of engineering." This statement has two implications for science education standards in general and for this report's framework in particular. The first is that students should learn how scientific knowledge is acquired and how scientific explanations are developed. The second is that students should learn how science is utilized, in particular through the engineering design process, and they should come to appreciate the distinctions and relationships between engineering, technology, and applications of science (ETS). These three terms are defined in Box 8-1.

Chapter 3 describes how an understanding of engineering practices can develop as they are used in the classroom to help students acquire and apply science knowledge. There is also a domain of knowledge related to these practices, and it constitutes the framework's first ETS core idea—ETS1: Engineering Design. Although there is not yet broad agreement on the full set of core ideas in engineering [1], an emerging consensus is that design is a central practice of engineering; indeed, design is the focus of the vast majority of K-12 engineering curricula currently in use. The committee is aware that engineers not only design new technologies, but they also sometimes fabricate, operate, inspect, and maintain them. However, from a teaching and learning point of view, it is the iterative cycle of design that offers the greatest potential for applying science knowledge in the

Copyright National Academy of Sciences. All rights reserved.

BOX 8-1

DEFINITIONS OF TECHNOLOGY, ENGINEERING, AND APPLICATIONS OF SCIENCE

Technology is any modification of the natural world made to fulfill human needs or desires [2].

Engineering is a systematic and often iterative approach to designing objects, processes, and systems to meet human needs and wants [2].

An application of science is any use of scientific knowledge for a specific purpose, whether to do more science; to design a product, process, or medical treatment; to develop a new technology; or to predict the impacts of human actions.

classroom and engaging in engineering practices. The components of this core idea include understanding how engineering problems are defined and delimited, how models can be used to develop and refine possible solutions to a design problem, and what methods can be employed to optimize a design.

The second ETS core idea calls for students to explore, as its name implies, the "Links Among Engineering, Technology, Science, and Society" (ETS2). The applications of science knowledge and practices to engineering, as well as to such areas as medicine and agriculture, have contributed to the technologies and the systems that support them that serve people today. Insights gained from scientific discovery have altered the ways in which buildings, bridges, and cities are constructed; changed the operations of factories; led to new methods of generating and distributing energy; and created new modes of travel and communication. Scientific insights have informed methods of food production, waste disposal, and the diagnosis and treatment of disease. In other words, science-based, or science-improved, designs of technologies and systems affect the ways in which people interact with each other and with the environment, and thus these designs deeply influence society.

In turn, society influences science and engineering. Societal decisions, which may be shaped by a variety of economic, political, and cultural factors, establish goals and priorities for technologies' improvement or replacement. Such decisions also set limits—in controlling the extraction of raw materials, for example, or in setting allowable emissions of pollution from mining, farming, and industry. Goals, priorities, and limits are needed for regulating new technologies, which can

Copyright National Academy of Sciences. All rights reserved.

have deep impacts on society and the environment. The impacts may not have been anticipated when the technologies were introduced (e.g., refrigerant gases that depleted stratospheric ozone) or may build up over time to levels that require mitigation (toxic pesticides, lead in gasoline). Thus the balancing of technologies' costs, benefits, and risks is a critical element of ETS2. Box 8-2 summarizes the framework's two ETS core ideas and their components.

The fields of science and engineering are mutually supportive. New technologies expand the reach of science, allowing the study of realms previously inaccessible to investigation; scientists depend on the work of engineers to produce the instruments and computational tools they need to conduct research. Engineers in turn depend on the work of scientists to understand how different technologies work so they can be improved; scientific discoveries are exploited to create new technologies in the first place. Scientists and engineers often work together in teams, especially in new fields, such as nanotechnology or synthetic biology that blur the lines between science and engineering. Students should come to understand these interactions and at increasing levels of sophistication as they mature. Their appreciation of the interface of science, engineering, and society should give them deeper insights into local, national, and global issues.

BOX 8-2

CORE AND COMPONENT IDEAS IN ENGINEERING, TECHNOLOGY, AND APPLICATIONS OF SCIENCE

Core Idea ETS1: Engineering Design

ETS1.A: Defining and Delimiting an Engineering Problem

ETS1.B: Developing Possible Solutions

ETS1.C: Optimizing the Design Solution

Core Idea ETS2: Links Among Engineering, Technology, Science, and Society

ETS2.A: Interdependence of Science, Engineering, and Technology

ETS2.B: Influence of Engineering, Technology, and Science on Society and the Natural World

Copyright National Academy of Sciences. All rights reserved.

The 2010 National Academy of Engineering report *Standards for K-12 Engineering Education?* [1] concluded that it is not appropriate at present to develop standalone K-12 engineering standards. But the report also made it clear that engineering concepts and skills are already embedded in existing standards for science and technology education, at both the state and national levels—and the report recommended that this practice continue. In addition, it affirmed the value of teaching engineering ideas, particularly engineering design, to young students.

In line with those conclusions and recommendations, the goal of this section of the framework—and of this chapter—is not to replace current K-12 engineering and technology courses. The chapter's goal is rather to strengthen the science education provided to K-12 students by making the connections between engineering, technology, and applications of science explicit, both for standards developers and curriculum developers. In that way, we hope to ensure that all students, whatever their path through K-12 education, gain an appreciation of these connections.

Core Idea ETS1 Engineering Design

How do engineers solve problems?

The design process—engineers' basic approach to problem solving—involves many different practices. They include problem definition, model development and use, investigation, analysis and interpretation of data, application of mathematics and computational thinking, and determination of solutions. These engineering practices incorporate specialized knowledge about criteria and constraints, modeling and analysis, and optimization and trade-offs.

ETS1.A: DEFINING AND DELIMITING AN ENGINEERING PROBLEM

What is a design for?
What are the criteria and constraints of a successful solution?

The engineering design process begins with the identification of a problem to solve and the specification of clear goals, or criteria, that the final product or system must meet. Criteria, which typically reflect the needs of the expected end-user of a technology or process, address such things as how the product or system will function (what job it will perform and how), its durability, and its cost. Criteria should be quantifiable whenever possible and stated so that one can tell if a given design meets them.

Copyright National Academy of Sciences. All rights reserved.

Engineers must contend with a variety of limitations, or constraints, when they engage in design. Constraints, which frame the salient conditions under which the problem must be solved, may be physical, economic, legal, political, social, ethical, aesthetic, or related to time and place. In terms of quantitative measurements, constraints may include limits on cost, size, weight, or performance, for example. And although constraints place restrictions on a design, not all of them are permanent or absolute.

Grade Band End Points for ETS1.A

By the end of grade 2. A situation that people want to change or create can be approached as a problem to be solved through engineering. Such problems may have many acceptable solutions. Asking questions, making observations, and gathering information are helpful in thinking about problems. Before beginning to design a solution, it is important to clearly understand the problem.

By the end of grade 5. Possible solutions to a problem are limited by available materials and resources (constraints). The success of a designed solution is determined by considering the desired features of a solution (criteria). Different proposals for solutions can be compared on the basis of how well each one meets the specified criteria for success or how well each takes the constraints into account.

By the end of grade 8. The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that are likely to limit possible solutions (e.g., familiarity with the local climate may rule out certain plants for the school garden).

By the end of grade 12. Design criteria and constraints, which typically reflect the needs of the end-user of a technology or process, address such things as the product's or system's function (what job it will perform and how), its durability, and limits on its size and cost. Criteria and constraints also include satisfying any requirements set by society, such as taking issues of risk mitigation into account, and they should be quantified to the extent possible and stated in such a way that one can tell if a given design meets them.

Humanity faces major global challenges today, such as the need for supplies of clean water and food or for energy sources that minimize pollution, which can be addressed through engineering. These global challenges also may

Copyright National Academy of Sciences. All rights reserved.

have manifestations in local communities. But whatever the scale, the first thing that engineers do is define the problem and specify the criteria and constraints for potential solutions.

ETS1.B: DEVELOPING POSSIBLE SOLUTIONS

What is the process for developing potential design solutions?

The creative process of developing a new design to solve a problem is a central element of engineering. This process may begin with a relatively open-ended phase during which new ideas are generated both by individuals and by group processes such as brainstorming. Before long, the process must move to the specification of solutions that meet the criteria and constraints at hand. Initial ideas may be communicated through informal sketches or diagrams, although they typically become more formalized through models. The ability to build and use physical, graphical, and mathematical models is an essential part of translating a design idea into a finished product, such as a machine, building, or any other working system. Because each area of engineering focuses on particular types of systems (e.g., mechanical, electrical, biotechnological), engineers become expert in the elements that such systems need. But whatever their fields, all engineers use models to help develop and communicate solutions to design problems.

Models allow the designer to better understand the features of a design problem, visualize elements of a possible solution, predict a design's performance, and guide the development of feasible solutions (or, if possible, the optimal solution). A physical model can be manipulated and tested for parameters of interest, such as strength, flexibility, heat conduction, fit with other components, and durability. Scale models and prototypes are particular types of physical models. Graphical models, such as sketches and drawings, permit engineers to easily share and discuss design ideas and to rapidly revise their thinking based on input from others.

Mathematical models allow engineers to estimate the effects of a change in one feature of the design (e.g., material composition, ambient temperature) on other features, or on performance as a whole, before the designed product

Copyright National Academy of Sciences. All rights reserved.

Models allow the designer to better understand the features of a design problem, visualize elements of a possible solution, predict a design's performance, and guide the development of feasible solutions.

is actually built. Mathematical models are often embedded in computer-based simulations. Computer-aided design (CAD) and computer-aided manufacturing (CAM) are modeling tools commonly used in engineering.

Data from models and experiments can be analyzed to make decisions about modifying a design. The analysis may reveal performance information, such as which criteria a design meets, or predict how well the overall designed system or system component will behave under certain conditions. If analysis reveals that the predicted performance does not align with desired criteria, the design can be adjusted.

Grade Band Endpoints for ETS1.B

By the end of grade 2. Designs can be conveyed through sketches, drawings, or physical models. These representations are useful in communicating ideas for a problem's solutions to other people. To design something complicated, one may need to break the problem into parts and attend to each part separately but must then bring the parts together to test the overall plan.

By the end of grade 5. Research on a problem should be carried out—for example, through Internet searches, market research, or field observations—before beginning to design a solution. An often productive way to generate ideas is for people to work together to brainstorm, test, and refine possible solutions. Testing a solution involves investigating how well it performs under a range of likely conditions. Tests are often designed to identify failure points or difficulties, which suggest the elements of the design that need to be improved. At whatever stage, communicating with peers about proposed solutions is an important part of the design process, and shared ideas can lead to improved designs.

There are many types of models, ranging from simple physical models to computer models. They can be used to investigate how a design might work, communicate the design to others, and compare different designs.

Copyright National Academy of Sciences. All rights reserved.

By the end of grade 8. A solution needs to be tested, and then modified on the basis of the test results, in order to improve it. There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. Sometimes parts of different solutions can be combined to create a solution that is better than any of its predecessors. In any case, it is important to be able to communicate and explain solutions to others.

Models of all kinds are important for testing solutions, and computers are a valuable tool for simulating systems. Simulations are useful for predicting what would happen if various parameters of the model were changed, as well as for making improvements to the model based on peer and leader (e.g., teacher) feedback.

By the end of grade 12. Complicated problems may need to be broken down into simpler components in order to develop and test solutions. When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts. Testing should lead to improvements in the design through an iterative procedure.

Both physical models and computers can be used in various ways to aid in the engineering design process. Physical models, or prototypes, are helpful in testing product ideas or the properties of different materials. Computers are useful for a variety of purposes, such as in representing a design in 3-D through CAD software; in troubleshooting to identify and describe a design problem; in running simulations to test different ways of solving a problem or to see which one is most efficient or economical; and in making a persuasive presentation to a client about how a given design will meet his or her needs.

ETS1.C: OPTIMIZING THE DESIGN SOLUTION

How can the various proposed design solutions be compared and improved?

Copyright National Academy of Sciences. All rights reserved.

Multiple solutions to an engineering design problem are always possible because there is more than one way to meet the criteria and satisfy the constraints. But the aim of engineering is not simply to design a solution to a problem but to design the best solution. Determining what constitutes "best," however, requires value judgments, given that one person's view of the optimal solution may differ from another's.

Optimization often requires making trade-offs among competing criteria. For example, as one criterion (such as lighter weight) is enhanced, another (such as unit cost) might be sacrificed (i.e., cost may be increased due to the higher cost of lightweight materials). In effect, one criterion is devalued or traded off for another that is deemed more important. When multiple possible design options are under consideration, with each optimized for different criteria, engineers may use a trade-off matrix to compare the overall advantages and disadvantages of the different proposed solutions.

The decision as to which criteria are critical and which ones can be traded off is a judgment based on the situation and the perceived needs of the end-user of the product or system. Because many factors—including environmental or health impacts, available technologies, and the expectations of users—change over time and vary from place to place, a design solution that is considered optimal at one time and place may appear far from optimal at other times and places. Thus different designs, each of them optimized for different conditions, are often needed.

Grade Band Endpoints for ETS1.C

By the end of grade 2. Because there is always more than one possible solution to a problem, it is useful to compare designs, test them, and discuss their strengths and weaknesses.

By the end of grade 5. Different solutions need to be tested in order to determine which of them best solves the problem, given the criteria and the constraints.

By the end of grade 8. There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. Comparing different designs could involve running them through the same kinds of tests and systematically recording the results to determine which design performs best. Although one design may not perform the best across all tests, identifying the characteristics of the design that performed the best in each test can provide useful information for the redesign process—that is, some of those characteristics may be

Copyright National Academy of Sciences. All rights reserved.

incorporated into the new design. This iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution. Once such a suitable solution is determined, it is important to describe that solution, explain how it was developed, and describe the features that make it successful.

By the end of grade 12. The aim of engineering is not simply to find a solution to a problem but to design the best solution under the given constraints and criteria. Optimization can be complex, however, for a design problem with numerous desired qualities or outcomes. Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed. The comparison of multiple designs can be aided by a trade-off matrix. Sometimes a numerical weighting system can help evaluate a design against multiple criteria. When evaluating solutions, all relevant considerations, including cost, safety, reliability, and aesthetic, social, cultural, and environmental impacts, should be included. Testing should lead to design improvements through an iterative process, and computer simulations are one useful way of running such tests.

Core Idea ETS2 Links Among Engineering, Technology, Science, and Society

How are engineering, technology, science, and society interconnected?

New insights from science often catalyze the emergence of new technologies and their applications, which are developed using engineering design. In turn, new technologies open opportunities for new scientific investigations. Together, advances in science, engineering, and technology can have—and indeed have had—profound effects on human society, in such areas as agriculture, transportation, health care, and communication, and on the natural environment. Each system can change significantly when new technologies are introduced, with both desired effects and unexpected outcomes.

ETS2.A: INTERDEPENDENCE OF SCIENCE, ENGINEERING, AND TECHNOLOGY

What are the relationships among science, engineering, and technology?

The fields of science and engineering are mutually supportive, and scientists and engineers often work together in teams, especially in fields at the borders of science and

Copyright National Academy of Sciences. All rights reserved.

Together, advances in science, engineering, and technology can have—and indeed have had—profound effects on human society.

engineering. Advances in science offer new capabilities, new materials, or new understanding of processes that can be applied through engineering to produce advances in technology. Advances in technology, in turn, provide scientists with new capabilities to probe the natural world at larger or smaller scales; to record, manage, and analyze data; and to model ever more complex systems with greater precision. In addition, engineers' efforts to develop or improve technologies often raise new questions for scientists' investigation.

Grade Band Endpoints for ETS2.A

By the end of grade 2. People encounter questions about the natural world every day. There are many types of tools produced by engineering that can be used in science to help answer these questions through observation or measurement. Observations and measurements are also used in engineering to help test and refine design ideas.

By the end of grade 5. Tools and instruments (e.g., rulers, balances, thermometers, graduated cylinders, telescopes, microscopes) are used in scientific exploration to gather data and help answer questions about the natural world. Engineering design can develop and improve such technologies. Scientific discoveries about the natural world can often lead to new and improved technologies, which are developed through the engineering design process. Knowledge of relevant scientific concepts and research findings is important in engineering.

By the end of grade 8. Engineering advances have led to important discoveries in virtually every field of science, and scientific discoveries have led to the development of entire industries and engineered systems. In order to design better technologies, new science may need to be explored (e.g., materials research prompted by desire for better batteries or solar cells, biological questions raised by medical problems). Technologies in turn extend the measurement, exploration, modeling, and computational capacity of scientific investigations.

By the end of grade 12. Science and engineering complement each other in the cycle known as research and development (R&D). Many R&D projects may

Copyright National Academy of Sciences. All rights reserved.

involve scientists, engineers, and others with wide ranges of expertise. For example, developing a means for safely and securely disposing of nuclear waste will require the participation of engineers with specialties in nuclear engineering, transportation, construction, and safety; it is likely to require as well the contributions of scientists and other professionals from such diverse fields as physics, geology, economics, psychology, and sociology.

ETS2.B: INFLUENCE OF ENGINEERING, TECHNOLOGY, AND SCIENCE ON SOCIETY AND THE NATURAL WORLD

How do science, engineering, and the technologies that result from them affect the ways in which people live? How do they affect the natural world?

From the earliest forms of agriculture to the latest technologies, all human activity has drawn on natural resources and has had both short- and long-term consequences, positive as well as negative, for the health of both people and the natural environment. These consequences have grown stronger in recent human history. Society has changed dramatically, and human populations and longevity have increased, as advances in science and engineering have influenced the ways in which people interact with one another and with their surrounding natural environment.

Science and engineering affect diverse domains—agriculture, medicine, housing, transportation, energy production, water availability, and land use, among others. The results often entail deep impacts on society and the environment, including some that may not have been anticipated when they were introduced or that may build up over time to levels that require attention. Decisions about the use of any new technology thus involve a balancing of costs, benefits, and risks—aided, at times, by science and engineering. Mathematical modeling, for example, can help provide insight into the consequences of actions beyond the scale of place, time, or system complexity that individual human judgments can readily encompass, thereby informing both personal and societal decision making.

Human populations and longevity have increased, as advances in science and engineering have influenced the ways in which people interact with one another and with their surrounding natural environment.

Copyright National Academy of Sciences. All rights reserved.

Not only do science and engineering affect society, but society's decisions (whether made through market forces or political processes) influence the work of scientists and engineers. These decisions sometimes establish goals and priorities for improving or replacing technologies; at other times they set limits, such as in regulating the extraction of raw materials or in setting allowable levels of pollution from mining, farming, and industry.

Grade Band Endpoints for ETS2.B

By the end of grade 2. People depend on various technologies in their lives; human life would be very different without technology. Every human-made product is designed by applying some knowledge of the natural world and is built by using materials derived from the natural world, even when the materials are not themselves natural—for example, spoons made from refined metals. Thus, developing and using technology has impacts on the natural world.

By the end of grade 5. Over time, people's needs and wants change, as do their demands for new and improved technologies. Engineers improve existing technologies or develop new ones to increase their benefits (e.g., better artificial limbs), to decrease known risks (e.g., seatbelts in cars), and to meet societal demands (e.g., cell phones). When new technologies become available, they can bring about changes in the way people live and interact with one another.

By the end of grade 8. All human activity draws on natural resources and has both short- and long-term consequences, positive as well as negative, for the health of both people and the natural environment. The uses of technologies and any limitations on their use are driven by individual or societal needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions. Thus technology use varies from region to region and over time. Technologies that are beneficial for a certain purpose may later be seen to have impacts (e.g., health-related, environmental) that were not foreseen. In such cases, new regulations on use or new technologies (to mitigate the impacts or eliminate them) may be required.

Copyright National Academy of Sciences. All rights reserved.

By the end of grade 12. Modern civilization depends on major technological systems, including those related to agriculture, health, water, energy, transportation, manufacturing, construction, and communications. Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks. Widespread adoption of technological innovations often depends on market forces or other societal demands, but it may also be subject to evaluation by scientists and engineers and to eventual government regulation. New technologies can have deep impacts on society and the environment, including some that were not anticipated or that may build up over time to a level that requires attention or mitigation. Analysis of costs, environmental impacts, and risks, as well as of expected benefits, is a critical aspect of decisions about technology use.

REFERENCES

1. National Academy of Engineering. (2010). *Standards for K-12 Engineering Education?* Committee on Standards for K-12 Engineering Education. Washington, DC: The National Academies Press.
2. National Assessment Governing Board. (2010). *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress.* Available: http://www.nagb.org/publications/frameworks/prepub_naep_tel_framework_2014.pdf [April 2011].

Copyright National Academy of Sciences. All rights reserved.