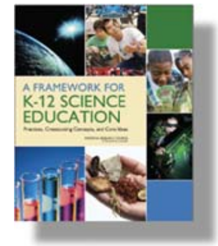
Practice 1 Asking Questions and Defining Problems



Questions are the engine that drive science and engineering.
Science asks

- What exists and what happens?
- Why does it happen?
- How does one know?

Engineering asks

- What can be done to address a particular human need or want?
- How can the need be better specified?
- What tools and technologies are available, or could be developed, for addressing this need?

Both science and engineering ask

- How does one communicate about phenomena, evidence, explanations, and design solutions?

Asking questions is essential to developing scientific habits of mind. Even for individuals who do not become scientists or engineers, the ability to ask well defined questions is an important component of science literacy, helping to make them critical consumers of scientific knowledge.

Scientific questions arise in a variety of ways. They can be driven by curiosity about the world (e.g., Why is the sky blue?). They can be inspired by a model's or theory's predictions or by attempts to extend or refine a model or theory (e.g., How does the particle model of matter explain the incompressibility of liquids?). Or they can result from the need to provide better solutions to a problem. For example, the question of why it is impossible to siphon water above a height of 32 feet led Evangelista Torricelli (17th-century inventor of the barometer) to his discoveries about the atmosphere and the identification of a vacuum.

Questions are also important in engineering. Engineers must be able to ask probing questions in order to define an engineering problem. For example, they may ask: What is the need or desire that underlies the problem? What are the criteria (specifications) for a successful solution? What are the constraints? Other questions arise when generating possible solutions: Will this solution meet the design criteria? Can two or more ideas be combined to produce a better solution? What are the possible trade-offs? And more questions arise when testing solutions: Which ideas should be tested? What evidence is needed to show which idea is optimal under the given constraints?

The experience of learning science and engineering should therefore develop students' ability to ask—and indeed, encourage them to ask—well-formulated questions that can be investigated empirically. Students also need to recognize the distinction between questions that can be answered empirically and those that are answerable only in other domains of knowledge or human experience.

GOALS

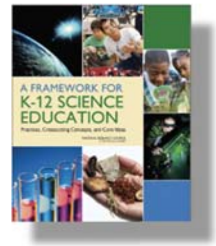
By grade 12, students should be able to

- Ask questions about the natural and human-built worlds—for example: Why are there seasons? What do bees do? Why did that structure collapse? How is electric power generated?
- Distinguish a scientific question (e.g., Why do helium balloons rise?) from a nonscientific question (Which of these colored balloons is the prettiest?).
- Formulate and refine questions that can be answered empirically in a science classroom and use them to design an inquiry or construct a pragmatic solution.
- Ask probing questions that seek to identify the premises of an argument, request further elaboration, refine a research question or engineering problem, or challenge the interpretation of a data set—for example: How do you know? What evidence supports that argument?
- Note features, patterns, or contradictions in observations and ask questions about them.
- For engineering, ask questions about the need or desire to be met in order to define constraints and specifications for a solution.

PROGRESSION

Students at any grade level should be able to ask questions of each other about the texts they read, the features of the phenomena they observe, and the conclusions they draw from their models or scientific investigations. For engineering, they should ask questions to define the problem to be solved and to elicit ideas that lead to the constraints and specifications for its solution. As they progress across the grades, their questions should become more relevant, focused, and sophisticated. Facilitating such evolution will require a classroom culture that respects and values good questions, that offers students opportunities to refine their questions and questioning strategies, and that incorporates the teaching of effective questioning strategies across all grade levels. As a result, students will become increasingly proficient at posing questions that request relevant empirical evidence; that seek to refine a model, an explanation, or an engineering problem; or that challenge the premise of an argument or the suitability of a design.

Practice 2 Developing and Using Models



Scientists construct mental and conceptual models of phenomena. Mental models are internal, personal, idiosyncratic, incomplete, unstable, and essentially functional. They serve the purpose of being a tool for thinking with, making predictions, and making sense of experience. Conceptual models, the focus of this section, are, in contrast, explicit representations that are in some ways analogous to the phenomena they represent. Conceptual models allow scientists and engineers to better visualize and understand a phenomenon under investigation or develop a possible solution to a design problem. Used in science and engineering as either structural, functional, or behavioral analogs, albeit simplified, conceptual models include diagrams, physical replicas, mathematical representations, analogies, and computer simulations. Although they do not correspond exactly to the more complicated entity being modeled, they do bring certain features into focus while minimizing or obscuring others. Because all models contain approximations and assumptions that limit the range of validity of their application and the precision of their predictive power, it is important to recognize their limitations.

Conceptual models are in some senses the external articulation of the mental models that scientists hold and are strongly interrelated with mental models. Building an understanding of models and their role in science helps students to construct and revise mental models of phenomena. Better mental models, in turn, lead to a deeper understanding of science and enhanced scientific reasoning.

Scientists use models (from here on, for the sake of simplicity, we use the term “models” to refer to conceptual models rather than mental models) to represent their current understanding of a system (or parts of a system) under study, to aid in the development of questions and explanations, and to communicate ideas to others [13]. Some of the models used by scientists are mathematical; for example, the ideal gas law is an equation derived from the model of a gas as a set of point masses engaged in perfectly elastic collisions with each other and the walls of the container—which is a simplified model based on the atomic theory of matter. For more complex systems, mathematical representations of physical systems are used to create computer simulations, which enable scientists to predict the behavior of otherwise intractable systems—for example, the effects of increasing atmospheric levels of carbon dioxide on agriculture in different regions of the world. Models can be evaluated and refined through an iterative cycle of comparing their predictions with the real world and then adjusting them, thereby potentially yielding insights into the phenomenon being modeled.

Engineering makes use of models to analyze existing systems; this allows engineers to see where or under what conditions flaws might develop or to test possible solutions to a new problem. Engineers also use models to visualize a design and take it to a higher level of refinement, to communicate a design’s features to others, and as prototypes for testing design performance. Models, particularly modern computer simulations that encode relevant physical laws and properties of materials, can be especially helpful both in realizing and testing designs for structures, such as buildings, bridges, or aircraft, that are expensive to construct and that must survive extreme conditions that occur only on rare occasions. Other types of engineering problems also benefit from use of specialized computer-based simulations in their design and testing phases. But as in science, engineers who use models must be aware of their intrinsic limitations and test them against known situations to ensure that they are reliable.

GOALS

By grade 12, students should be able to

- Construct drawings or diagrams as representations of events or systems—for example, draw a picture of an insect with labeled features, represent what happens to the water in a puddle as it is warmed by the sun, or represent a simple physical model of a real-world object and use it as the basis of an explanation or to make predictions about how the system will behave in specified circumstances.
- Represent and explain phenomena with multiple types of models—for example, represent molecules with 3-D models or with bond diagrams—and move flexibly between model types when different ones are most useful for different purposes.
- Discuss the limitations and precision of a model as the representation of a system, process, or design and suggest ways in which the model might be improved to better fit available evidence or better reflect a design's specifications. Refine a model in light of empirical evidence or criticism to improve its quality and explanatory power.
- Use (provided) computer simulations or simulations developed with simple simulation tools as a tool for understanding and investigating aspects of a system, particularly those not readily visible to the naked eye.
- Make and use a model to test a design, or aspects of a design, and to compare the effectiveness of different design solutions.

PROGRESSION

Modeling can begin in the earliest grades, with students' models progressing from concrete "pictures" and/or physical scale models (e.g., a toy car) to more abstract representations of relevant relationships in later grades, such as a diagram representing forces on a particular object in a system. Students should be asked to use diagrams, maps, and other abstract models as tools that enable them to elaborate on their own ideas or findings and present them to others [15]. Young students should be encouraged to devise pictorial and simple graphical representations of the findings of their investigations and to use these models in developing their explanations of what occurred.

More sophisticated types of models should increasingly be used across the grades, both in instruction and curriculum materials, as students progress through their science education. The quality of a student-developed model will be highly dependent on prior knowledge and skill and also on the student's understanding of the system being modeled, so students should be expected to refine their models as their understanding develops. Curricula will need to stress the role of models explicitly and provide students with modeling tools (e.g., Model-It, agent-based modeling such as NetLogo, spreadsheet models), so that students come to value this core practice and develop a level of facility in constructing and applying appropriate models.

Practice 3 Planning and Carrying Out Investigations

Scientists and engineers investigate and observe the world with essentially two goals: (1) to systematically describe the world and (2) to develop and test theories and explanations of how the world works. In the first, careful observation and description often lead to identification of features that need to be explained or questions that need to be explored.

The second goal requires investigations to test explanatory models of the world and their predictions and whether the inferences suggested by these models are supported by data. Planning and designing such investigations require the ability to design experimental or observational inquiries that are appropriate to answering the question being asked or testing a hypothesis that has been formed. This process begins by identifying the relevant variables and considering how they might be observed, measured, and controlled (constrained by the experimental design to take particular values).

Planning for controls is an important part of the design of an investigation. In laboratory experiments, it is critical to decide which variables are to be treated as results or outputs and thus left to vary at will and which are to be treated as input conditions and hence controlled. In many cases, particularly in the case of field observations, such planning involves deciding what can be controlled and how to collect different samples of data under different conditions, even though not all conditions are under the direct control of the investigator.

Decisions must also be made about what measurements should be taken, the level of accuracy required, and the kinds of instrumentation best suited to making such measurements. As in other forms of inquiry, the key issue is one of precision—the goal is to measure the variable as accurately as possible and reduce sources of error. The investigator must therefore decide what constitutes a sufficient level of precision and what techniques can be used to reduce both random and systematic error.

GOALS

By grade 12, students should be able to

- Formulate a question that can be investigated within the scope of the classroom, school laboratory, or field with available resources and, when appropriate, frame a hypothesis (that is, a possible explanation that predicts a particular and stable outcome) based on a model or theory.
- Decide what data are to be gathered, what tools are needed to do the gathering, and how measurements will be recorded.
- Decide how much data are needed to produce reliable measurements and consider any limitations on the precision of the data.
- Plan experimental or field-research procedures, identifying relevant independent and dependent variables and, when appropriate, the need for controls.
- Consider possible confounding variables or effects and ensure that the investigation's design has controlled for them.

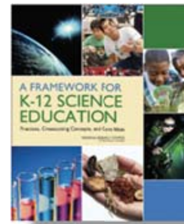
PROGRESSION

Students need opportunities to design investigations so that they can learn the importance of such decisions as what to measure, what to keep constant, and how to select or construct data collection instruments that are appropriate to the needs of an inquiry. They also need experiences that help them recognize that the laboratory is not the sole domain for legitimate scientific inquiry and that, for many scientists (e.g., earth scientists, ethologists, ecologists), the “laboratory” is the natural world where experiments are conducted and data are collected in the field.

In the elementary years, students’ experiences should be structured to help them learn to define the features to be investigated, such as patterns that suggest causal relationships (e.g., What features of a ramp affect the speed of a given ball as it leaves the ramp?). The plan of the investigation, what trials to make and how to record information about them, then needs to be refined iteratively as students recognize from their experiences the limitations of their original plan. These investigations can be enriched and extended by linking them to engineering design projects—for example, how can students apply what they have learned about ramps to design a track that makes a ball travel a given distance, go around a loop, or stop on an uphill slope. From the earliest grades, students should have opportunities to carry out careful and systematic investigations, with appropriately supported prior experiences that develop their ability to observe and measure and to record data using appropriate tools and instruments.

Students should have opportunities to plan and carry out several different kinds of investigations during their K-12 years. At all levels, they should engage in investigations that range from those structured by the teacher—in order to expose an issue or question that they would be unlikely to explore on their own (e.g., measuring specific properties of materials)—to those that emerge from students’ own questions. As they become more sophisticated, students also should have opportunities not only to identify questions to be researched but also to decide what data are to be gathered, what variables should be controlled, what tools or instruments are needed to gather and record data in an appropriate format, and eventually to consider how to incorporate measurement error in analyzing data. Older students should be asked to develop a hypothesis that predicts a particular and stable outcome and to explain their reasoning and justify their choice. By high school, any hypothesis should be based on a well-developed model or theory. In addition, students should be able to recognize that it is not always possible to control variables and that other methods can be used in such cases—for example, looking for correlations (with the understanding that correlations do not necessarily imply causality).

Practice 4 Analyzing and Interpreting Data



Once collected, data must be presented in a form that can reveal any patterns and relationships and that allows results to be communicated to others. Because raw data as such have little meaning, a major practice of scientists is to organize and interpret data through tabulating, graphing, or statistical analysis. Such analysis can bring out the meaning of data—and their relevance—so that they may be used as evidence.

Engineers, too, make decisions based on evidence that a given design will work; they rarely rely on trial and error. Engineers often analyze a design by creating a model or prototype and collecting extensive data on how it performs, including under extreme conditions. Analysis of this kind of data not only informs design decisions and enables the prediction or assessment of performance but also helps define or clarify problems, determine economic feasibility, evaluate alternatives, and investigate failures.

Spreadsheets and databases provide useful ways of organizing data, especially large data sets. The identification of relationships in data is aided by a range of tools, including tables, graphs, and mathematics. Tables permit major features of a large body of data to be summarized in a conveniently accessible form, graphs offer a means of visually summarizing data, and mathematics is essential for expressing relationships between different variables in the data set (see Practice 5 for further discussion of mathematics). Modern computer-based visualization tools often allow data to be displayed in varied forms and thus for learners to engage interactively with data in their analyses. In addition, standard statistical techniques can help to reduce the effect of error in relating one variable to another.

Students need opportunities to analyze large data sets and identify correlations. Increasingly, such data sets—involving temperature, pollution levels, and other scientific measurements—are available on the Internet. Moreover, information technology enables the capture of data beyond the classroom at all hours of the day. Such data sets extend the range of students' experiences and help to illuminate this important practice of analyzing and interpreting data.

GOALS

By grade 12, students should be able to

- Analyze data systematically, either to look for salient patterns or to test whether data are consistent with an initial hypothesis.
- Recognize when data are in conflict with expectations and consider what revisions in the initial model are needed.
- Use spreadsheets, databases, tables, charts, graphs, statistics, mathematics, and information and computer technology to collate, summarize, and display data and to explore relationships between variables, especially those representing input and output.
- Evaluate the strength of a conclusion that can be inferred from any data set, using appropriate grade-level mathematical and statistical techniques.
- Recognize patterns in data that suggest relationships worth investigating further. Distinguish between causal and correlational relationships.
- Collect data from physical models and analyze the performance of a design under a range of conditions.

PROGRESSION

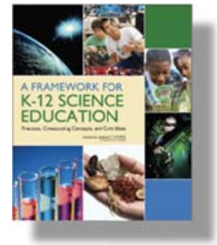
At the elementary level, students need support to recognize the need to record observations—whether in drawings, words, or numbers—and to share them with others. As they engage in scientific inquiry more deeply, they should begin to collect categorical or numerical data for presentation in forms that facilitate interpretation, such as tables and graphs. When feasible, computers and other digital tools should be introduced as a means of enabling this practice.

In middle school, students should have opportunities to learn standard techniques for displaying, analyzing, and interpreting data; such techniques include different types of graphs, the identification of outliers in the data set, and averaging to reduce the effects of measurement error. Students should also be asked to explain why these techniques are needed.

As students progress through various science classes in high school and their investigations become more complex, they need to develop skill in additional techniques for displaying and analyzing data, such as x-y scatterplots or crosstabulations to express the relationship between two variables. Students should be helped to recognize that they may need to explore more than one way to display their data in order to identify and present significant features. They also need opportunities to use mathematics and statistics to analyze features of data such as covariation. Also at the high school level, students should have the opportunity to use a greater diversity of samples of scientific data and to use computers or other digital tools to support this kind of analysis.

Students should be expected to use some of these same techniques in engineering as well. When they do so, it is important that they are made cognizant of the purpose of the exercise—that any data they collect and analyze are intended to help validate or improve a design or decide on an optimal solution.

Practice 5 Using Mathematics and Computational Thinking



Mathematics and computational tools are central to science and engineering. Mathematics enables the numerical representation of variables, the symbolic representation of relationships between physical entities, and the prediction of outcomes. Mathematics provides powerful models for describing and predicting such phenomena as atomic structure, gravitational forces, and quantum mechanics. Since the mid-20th century, computational theories, information and computer technologies, and algorithms have revolutionized virtually all scientific and engineering fields. These tools and strategies allow scientists and engineers to collect and analyze large data sets, search for distinctive patterns, and identify relationships and significant features in ways that were previously impossible. They also provide powerful new techniques for employing mathematics to model complex phenomena— for example, the circulation of carbon dioxide in the atmosphere and ocean.

Mathematics and computation can be powerful tools when brought to bear in a scientific investigation. Mathematics serves pragmatic functions as a tool—both a communicative function, as one of the languages of science, and a structural function, which allows for logical deduction. Mathematics enables ideas to be expressed in a precise form and enables the identification of new ideas about the physical world. For example, the concept of the equivalence of mass and energy emerged from the mathematical analysis conducted by Einstein, based on the premises of special relativity. The contemporary understanding of electromagnetic waves emerged from Maxwell's mathematical analysis of the behavior of electric and magnetic fields. Modern theoretical physics is so heavily imbued with mathematics that it would make no sense to try to divide it into mathematical and nonmathematical parts. In much of modern science, predictions and inferences have a probabilistic nature, so understanding the mathematics of probability and of statistically derived inferences is an important part of understanding science.

Computational tools enhance the power of mathematics by enabling calculations that cannot be carried out analytically. For example, they allow the development of simulations, which combine mathematical representations of multiple underlying phenomena to model the dynamics of a complex system. Computational methods are also potent tools for visually representing data, and they can show the results of calculations or simulations in ways that allow the exploration of patterns.

Engineering, too, involves mathematical and computational skills. For example, structural engineers create mathematical models of bridge and building designs, based on physical laws, to test their performance, probe their structural limits, and assess whether they can be completed within acceptable budgets. Virtually any engineering design raises issues that require computation for their resolution.

Although there are differences in how mathematics and computational thinking are applied in science and in engineering, mathematics often brings these two fields together by enabling engineers to apply the mathematical form of scientific theories and by enabling scientists to use powerful information technologies designed by engineers. Both kinds of professionals can thereby accomplish investigations and analyses and build complex models, which might otherwise be out of the question.

Mathematics (including statistics) and computational tools are essential for data analysis, especially for large data sets. The abilities to view data from different perspectives and with different graphical representations, to test relationships between variables, and to explore the interplay of diverse external conditions all require mathematical skills that are enhanced and extended with computational skills.

GOALS

By grade 12, students should be able to

- Recognize dimensional quantities and use appropriate units in scientific applications of mathematical formulas and graphs.
- Express relationships and quantities in appropriate mathematical or algorithmic forms for scientific modeling and investigations.
- Recognize that computer simulations are built on mathematical models that incorporate underlying assumptions about the phenomena or systems being studied.
- Use simple test cases of mathematical expressions, computer programs, or simulations—that is, compare their outcomes with what is known about the real world—to see if they "make sense."
- Use grade-level-appropriate understanding of mathematics and statistics in analyzing data.

PROGRESSION

Increasing students' familiarity with the role of mathematics in science is central to developing a deeper understanding of how science works. As soon as students learn to count, they can begin using numbers to find or describe patterns in nature. At appropriate grade levels, they should learn to use such instruments as rulers, protractors, and thermometers for the measurement of variables that are best represented by a continuous numerical scale, to apply mathematics to interpolate values, and to identify features—such as maximum, minimum, range, average, and median—of simple data sets.

A significant advance comes when relationships are expressed using equalities first in words and then in algebraic symbols—for example, shifting from distance traveled equals velocity multiplied by time elapsed to $s = vt$. Students should have opportunities to explore how such symbolic representations can be used to represent data, to predict outcomes, and eventually to derive further relationships using mathematics. Students should gain experience in using computers to record measurements taken with computer-connected probes or instruments, thereby recognizing how this process allows multiple measurements to be made rapidly and recurrently. Likewise, students should gain experience in using computer programs to transform their data between various tabular and graphical forms, thereby aiding in the identification of patterns.

Students should thus be encouraged to explore the use of computers for data analysis, using simple data sets, at an early age. For example, they could use spreadsheets to record data and then perform simple and recurring calculations from those data, such as the calculation of average speed from measurements of positions at multiple times. Later work should introduce them to the use of mathematical relationships to build simple computer models, using appropriate supporting programs or information and computer technology tools. As students progress in their understanding of mathematics and computation, at every level the science classroom should be a place where these tools are progressively exploited.

Practice 6 Constructing Explanations and Designing Solutions

Because science seeks to enhance human understanding of the world, scientific theories are developed to provide explanations aimed at illuminating the nature of particular phenomena, predicting future events, or making inferences about past events. Science has developed explanatory theories, such as the germ theory of disease, the Big Bang theory of the origin of the universe, and Darwin's theory of the evolution of species. Although their role is often misunderstood—the informal use of the word "theory," after all, can mean a guess—*scientific* theories are constructs based on significant bodies of knowledge and evidence, are revised in light of new evidence, and must withstand significant scrutiny by the scientific community before they are widely accepted and applied. Theories are not mere guesses, and they are especially valued because they provide explanations for multiple instances.

In science, the term "hypothesis" is also used differently than it is in everyday language. A scientific hypothesis is neither a scientific theory nor a guess; it is a plausible explanation for an observed phenomenon that can predict what will happen in a given situation. A hypothesis is made based on existing theoretical understanding relevant to the situation and often also on a specific model for the system in question.

Scientific explanations are accounts that link scientific theory with specific observations or phenomena—for example, they explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them. Very often the theory is first represented by a specific model for the situation in question, and then a model-based explanation is developed. For example, if one understands the theory of how oxygen is obtained, transported, and utilized in the body, then a model of the circulatory system can be developed and used to explain why heart rate and breathing rate increase with exercise.

Engaging students with standard scientific explanations of the world— helping them to gain an understanding of the major ideas that science has developed— is a central aspect of science education. Asking students to demonstrate their own understanding of the implications of a scientific idea by developing their own explanations of phenomena, whether based on observations they have made or models they have developed, engages them in an essential part of the process by which conceptual change can occur. Explanations in science are a natural for such pedagogical uses, given their inherent appeals to simplicity, analogy, and empirical data (which may even be in the form of a thought experiment) [26, 27]. And explanations are especially valuable for the classroom because of, rather than in spite of, the fact that there often are competing explanations offered for the same phenomenon—for example, the recent gradual rise in the mean surface temperature on Earth. Deciding on the best explanation is a matter of argument that is resolved by how well any given explanation fits with all available data, how much it simplifies what would seem to be complex, and whether it produces a sense of understanding.

Because scientists achieve their own understanding by building theories and theory-based explanations with the aid of models and representations and by drawing on data and evidence, students should also develop some facility in constructing model- or evidence-based explanations. This is an essential step in building their own understanding of phenomena, in gaining greater appreciation of the explanatory power of the scientific theories that they are learning about in class, and in acquiring greater insight into how scientists operate.

In engineering, the goal is a design rather than an explanation. The process of developing a design is iterative and systematic, as is the process of developing an explanation or a theory in science. Engineers' activities, however, have elements that are distinct from those of scientists. These elements include specifying constraints and criteria for desired qualities of the solution, developing a design plan, producing and testing models or prototypes, selecting among alternative design features to optimize the achievement of design criteria, and refining design ideas based on the performance of a prototype or simulation.

GOALS

By grade 12, students should be able to

- Construct their own explanations of phenomena using their knowledge of accepted scientific theory and linking it to models and evidence.
- Use primary or secondary scientific evidence and models to support or refute an explanatory account of a phenomenon.
- Offer causal explanations appropriate to their level of scientific knowledge.

- Identify gaps or weaknesses in explanatory accounts (their own or those of others).

In their experience of engineering, students should have the opportunity to

- Solve design problems by appropriately applying their scientific knowledge.
- Undertake design projects, engaging in all steps of the design cycle and producing a plan that meets specific design criteria.
- Construct a device or implement a design solution.
- Evaluate and critique competing design solutions based on jointly developed and agreed-on design criteria.

PROGRESSION FOR EXPLANATION

Early in their science education, students need opportunities to engage in constructing and critiquing explanations. They should be encouraged to develop explanations of what they observe when conducting their own investigations and to evaluate their own and others' explanations for consistency with the evidence. For example, observations of the owl pellets they dissect should lead them to produce an explanation of owls' eating habits based on inferences made from what they find.

As students' knowledge develops, they can begin to identify and isolate variables and incorporate the resulting observations into their explanations of phenomena. Using their measurements of how one factor does or does not affect another, they can develop causal accounts to explain what they observe. For example, in investigating the conditions under which plants grow fastest, they may notice that the plants die when kept in the dark and seek to develop an explanation for this finding. Although the explanation at this level may be as simple as "plants die in the dark because they need light in order to live and grow," it provides a basis for further questions and deeper understanding of how plants utilize light that can be developed in later grades. On the basis of comparison of their explanation with their observations, students can appreciate that an explanation such as "plants need light to grow" fails to explain why they die when no water is provided. They should be encouraged to revisit their initial ideas and produce more complete explanations that account for more of their observations.

By the middle grades, students recognize that many of the explanations of science rely on models or representations of entities that are too small to see or too large to visualize. For example, explaining why the temperature of water does not increase beyond 100°C when heated requires students to envisage water as consisting of microscopic particles and that the energy provided by heating can allow fast-moving particles to escape despite the force of attraction holding the particles together. In the later stages of their education, students should also progress to using mathematics or simulations to construct an explanation for a phenomenon.

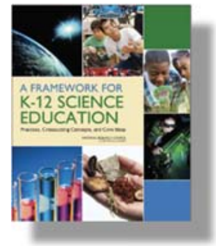
PROGRESSION FOR DESIGN

In some ways, children are natural engineers. They spontaneously build sand castles, dollhouses, and hamster enclosures, and they use a variety of tools and materials for their own playful purposes. Thus a common elementary school activity is to challenge children to use tools and materials provided in class to solve a specific challenge, such as constructing a bridge from paper and tape and testing it until failure occurs. Children's capabilities to design structures can then be enhanced by having them pay attention to points of failure and asking them to create and test redesigns of the bridge so that it is stronger. Furthermore, design activities should not be limited just to structural engineering but should also include projects that reflect other areas of engineering, such as the need to design a traffic pattern for the school parking lot or a layout for planting a school garden box.

In middle school, it is especially beneficial to engage students in engineering design projects in which they are expected to apply what they have recently learned in science—for example, using their now-familiar concepts of ecology to solve problems related to a school garden. Middle school students should also have opportunities to plan and carry out full engineering design projects in which they define problems in terms of criteria and constraints, research the problem to deepen their relevant knowledge, generate and test possible solutions, and refine their solutions through redesign.

At the high school level, students can undertake more complex engineering design projects related to major local, national or global issues. Increased emphasis should be placed on researching the nature of the given problems, on reviewing others' proposed solutions, on weighing the strengths and weaknesses of various alternatives, and on discerning possibly unanticipated effects.

Practice 7 Engaging in Argument from Evidence



Whether they concern new theories, proposed explanations of phenomena, novel solutions to technological problems, or fresh interpretations of old data, scientists and engineers use reasoning and argumentation to make their case. In science, the production of knowledge is dependent on a process of reasoning that requires a scientist to make a justified claim about the world. In response, other scientists attempt to identify the claim's weaknesses and limitations. Their arguments can be based on deductions from premises, on inductive generalizations of existing patterns, or on inferences about the best possible explanation. Argumentation is also needed to resolve questions involving, for example, the best experimental design, the most appropriate techniques of data analysis, or the best interpretation of a given data set.

In short, science is replete with arguments that take place both informally, in lab meetings and symposia, and formally, in peer review. Historical case studies of the origin and development of a scientific idea show how a new idea is often difficult to accept and has to be argued for—archetypal examples are the Copernican idea that Earth travels around the sun and Darwin's ideas about the origin of species. Over time, ideas that survive critical examination even in the light of new data attain consensual acceptance in the community, and by this process of discourse and argument science maintains its objectivity and progress [28].

The knowledge and ability to detect "bad science" [29, 30] are requirements both for the scientist and the citizen. Scientists must make critical judgments about their own work and that of their peers, and the scientist and the citizen alike must make evaluative judgments about the validity of science-related media reports and their implications for people's own lives and society [30]. Becoming a critical consumer of science is fostered by opportunities to use critique and evaluation to judge the merits of any scientifically based argument.

In engineering, reasoning and argument are essential to finding the best possible solution to a problem. At an early design stage, competing ideas must be compared (and possibly combined) to achieve an initial design, and the choices are made through argumentation about the merits of the various ideas pertinent to the design goals. At a later stage in the design process, engineers test their potential solution, collect data, and modify their design in an iterative manner. The results of such efforts are often presented as evidence to argue about the strengths and weaknesses of a particular design. Although the forms of argumentation are similar, the criteria employed in engineering are often quite different from those of science. For example, engineers might use cost-benefit analysis, an analysis of risk, an appeal to aesthetics, or predictions about market reception to justify why one design is better than another—or why an entirely different course of action should be followed.

GOALS

By grade 12, students should be able to

- Construct a scientific argument showing how data support a claim.
- Identify possible weaknesses in scientific arguments, appropriate to the students' level of knowledge, and discuss them using reasoning and evidence.
- Identify flaws in their own arguments and modify and improve them in response to criticism.
- Recognize that the major features of scientific arguments are claims, data, and reasons and distinguish these elements in examples.
- Explain the nature of the controversy in the development of a given scientific idea, describe the debate that surrounded its inception, and indicate why one particular theory succeeded.
- Explain how claims to knowledge are judged by the scientific community today and articulate the merits and limitations of peer review and the need for independent replication of critical investigations.
- Read media reports of science or technology in a critical manner so as to identify their strengths and weaknesses.

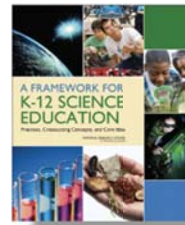
PROGRESSION

The study of science and engineering should produce a sense of the process of argument necessary for advancing and defending a new idea or an explanation of a phenomenon and the norms for conducting such arguments. In that spirit, students should argue for the explanations they construct, defend their interpretations of the associated data, and advocate for the designs they propose. Meanwhile, they should learn how to evaluate critically the scientific arguments of others and present counterarguments. Learning to argue scientifically offers students not only an opportunity to use their scientific knowledge in justifying an explanation and in identifying the weaknesses in others' arguments but also to build their own knowledge and understanding. Constructing and critiquing arguments are both a core process of science and one that supports science education, as research suggests that interaction with others is the most cognitively effective way of learning [31-33].

Young students can begin by constructing an argument for their own interpretation of the phenomena they observe and of any data they collect. They need instructional support to go beyond simply making claims—that is, to include reasons or references to evidence and to begin to distinguish evidence from opinion. As they grow in their ability to construct scientific arguments, students can draw on a wider range of reasons or evidence, so that their arguments become more sophisticated. In addition, they should be expected to discern what aspects of the evidence are potentially significant for supporting or refuting a particular argument.

Students should begin learning to critique by asking questions about their own findings and those of others. Later, they should be expected to identify possible weaknesses in either data or an argument and explain why their criticism is justified. As they become more adept at arguing and critiquing, they should be introduced to the language needed to talk about argument, such as claim, reason, data, etc. Exploration of historical episodes in science can provide opportunities for students to identify the ideas, evidence, and arguments of professional scientists. In so doing, they should be encouraged to recognize the criteria used to judge claims for new knowledge and the formal means by which scientific ideas are evaluated today. In particular, they should see how the practice of peer review and independent verification of claimed experimental results help to maintain objectivity and trust in science.

Practice 8 Obtaining, Evaluating, and Communicating Information



Being literate in science and engineering requires the ability to read and understand their literatures [34]. Science and engineering are ways of knowing that are represented and communicated by words, diagrams, charts, graphs, images, symbols, and mathematics [35]. Reading, interpreting, and producing text* are fundamental practices of science in particular, and they constitute at least half of engineers' and scientists' total working time [36].

Even when students have developed grade-level-appropriate reading skills, reading in science is often challenging to students for three reasons. First, the jargon of science texts is essentially unfamiliar; together with their often extensive use of, for example, the passive voice and complex sentence structure, many find these texts inaccessible [37]. Second, science texts must be read so as to extract information accurately. Because the precise meaning of each word or clause may be important, such texts require a mode of reading that is quite different from reading a novel or even a newspaper. Third, science texts are multimodal [38], using a mix of words, diagrams, charts, symbols, and mathematics to communicate. Thus understanding science texts requires much more than simply knowing the meanings of technical terms.

Communicating in written or spoken form is another fundamental practice of science; it requires scientists to describe observations precisely, clarify their thinking, and justify their arguments. Because writing is one of the primary means of communicating in the scientific community, learning how to produce scientific texts is as essential to developing an understanding of science as learning how to draw is to appreciating the skill of the visual artist. Indeed, the new *Common Core State Standards for English Language Arts & Literacy in History/Social Studies, Science, and Technical Subjects* [39] recognize that reading and writing skills are essential to science; the formal inclusion in this framework of this science practice reinforces and expands on that view. Science simply cannot advance if scientists are unable to communicate their findings clearly and persuasively. Communication occurs in a variety of formal venues, including peer-reviewed journals, books, conference presentations, and carefully constructed websites; it occurs as well through informal means, such as discussions, email messages, phone calls, and blogs. New technologies have extended communicative practices, enabling multidisciplinary collaborations across the globe that place even more emphasis on reading and writing. Increasingly, too, scientists are required to engage in dialogues with lay audiences about their work, which requires especially good communication skills.

Being a critical consumer of science and the products of engineering, whether as a lay citizen or a practicing scientist or an engineer, also requires the ability to read or view reports about science in the press or on the Internet and to recognize the salient science, identify sources of error and methodological flaws, and distinguish observations from inferences, arguments from explanations, and claims from evidence. All of these are constructs learned from engaging in a critical discourse around texts. Engineering proceeds in a similar manner because engineers need to communicate ideas and find and exchange information—for example, about new techniques or new uses of existing tools and materials. As in science, engineering communication involves not just written and spoken language; many engineering ideas are best communicated through sketches, diagrams, graphs, models, and products. Also in wide use are handbooks, specific to particular engineering fields, that provide detailed information, often in tabular form, on how best to formulate design solutions to commonly encountered engineering tasks. Knowing how to seek and use such informational resources is an important part of the engineer's skill set.

GOALS

By grade 12, students should be able to

- Use words, tables, diagrams, and graphs (whether in hard copy or electronically), as well as mathematical expressions, to communicate their understanding or to ask questions about a system under study.
- Read scientific and engineering text, including tables, diagrams, and graphs, commensurate with their scientific knowledge and explain the key ideas being communicated.
- Recognize the major features of scientific and engineering writing and speaking and be able to produce written and illustrated text or oral presentations that communicate their own ideas and accomplishments.
- Engage in a critical reading of primary scientific literature (adapted for classroom use) or of media reports of science and discuss the validity and reliability of the data, hypotheses, and conclusions.

PROGRESSION

Any education in science and engineering needs to develop students' ability to read and produce domain-specific text. As such, every science or engineering lesson is in part a language lesson, particularly reading and producing the genres of texts that are intrinsic to science and engineering.

Students need sustained practice and support to develop the ability to extract the meaning of scientific text from books, media reports, and other forms of scientific communication because the form of this text is initially unfamiliar— expository rather than narrative, often linguistically dense, and reliant on precise logical flows. Students should be able to interpret meaning from text, to produce text in which written language and diagrams are used to express scientific ideas, and to engage in extended discussion about those ideas.

From the very start of their science education, students should be asked to engage in the communication of science, especially regarding the investigations they are conducting and the observations they are making. Careful description of observations and clear statement of ideas, with the ability to both refine a statement in response to questions and to ask questions of others to achieve clarification of what is being said begin at the earliest grades. Beginning in upper elementary and middle school, the ability to interpret written materials becomes more important. Early work on reading science texts should also include explicit instruction and practice in interpreting tables, diagrams, and charts and coordinating information conveyed by them with information in written text. Throughout their science education, students are continually introduced to new terms, and the meanings of those terms can be learned only through opportunities to use and apply them in their specific contexts. Not only must students learn technical terms but also more general academic language, such as "analyze" or "correlation," which are not part of most students' everyday vocabulary and thus need specific elaboration if they are to make sense of scientific text. It follows that to master the reading of scientific material, students need opportunities to engage with such text and to identify its major features; they cannot be expected simply to apply reading skills learned elsewhere to master this unfamiliar genre effectively.

Students should write accounts of their work, using journals to record observations, thoughts, ideas, and models. They should be encouraged to create diagrams and to represent data and observations with plots and tables, as well as with written text, in these journals. They should also begin to produce reports or posters that present their work to others. As students begin to read and write more texts, the particular genres of scientific text—a report of an investigation, an explanation with supporting argumentation, an experimental procedure—will need to be introduced and their purpose explored. Furthermore, students should have opportunities to engage in discussion about observations and explanations and to make oral presentations of their results and conclusions as well as to engage in appropriate discourse with other students by asking questions and discussing issues raised in such presentations. Because the spoken language of such discussions and presentations is as far from their everyday language as scientific text is from a novel, the development both of written and spoken scientific explanation/ argumentation needs to proceed in parallel.

In high school, these practices should be further developed by providing students with more complex texts and a wider range of text materials, such as technical reports or scientific literature on the Internet. Moreover, students need opportunities to read and discuss general media reports with a critical eye and to read appropriate samples of adapted primary literature [40] to begin seeing how science is communicated by science practitioners.

In engineering, students likewise need opportunities to communicate ideas using appropriate combinations of sketches, models, and language. They should also create drawings to test concepts and communicate detailed plans; explain and critique models of various sorts, including scale models and prototypes; and present the results of simulations, not only regarding the planning and development stages but also to make compelling presentations of their ultimate solutions.