

4. Analyzing and Interpreting Data

Scientific investigations produce data that must be analyzed in order to derive meaning. Because data usually do not speak for themselves, scientists use a range of tools—including tabulation, graphical interpretation, visualization, and statistical analysis—to identify the significant features and patterns in the data. Sources of error are identified and the degree of certainty calculated. Modern technology makes the collection of large data sets much easier, thus providing many secondary sources for analysis.

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—that is, which design best solves the problem within the given constraints. Like scientists, engineers require a range of tools to identify the major patterns and interpret the results.

5. Using Mathematics and Computational Thinking

In **science**, mathematics and computation are fundamental tools for representing physical variables and their relationships. They are used for a range of tasks, such as constructing simulations, statistically analyzing data, and recognizing, expressing, and applying quantitative relationships. Mathematical and computational approaches enable predictions of the behavior of physical systems, along with the testing of such predictions. Moreover, statistical techniques are invaluable for assessing the significance of patterns or correlations.

In **engineering**, mathematical and computational representations of established relationships and principles are an integral part of design. For example, structural engineers create mathematically based analyses of designs to calculate whether they can stand up to the expected stresses of use and if they can be completed within acceptable budgets. Moreover, simulations of designs provide an effective test bed for the development of designs and their improvement.

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 instrument 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, an 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.

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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 cross-tabulations 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.

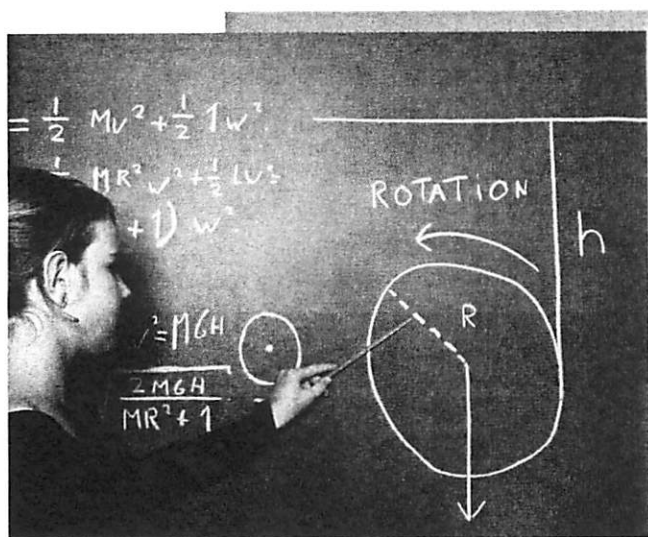
actice 5

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

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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.

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- 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.

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