Science for All Americans Online

Chapter 12: HABITS OF MIND

Throughout history, people have concerned themselves with the transmission of shared values, attitudes, and skills from one generation to the next. All three were taught long before formal schooling was invented. Even today, it is evident that family, religion, peers, books, news and entertainment media, and general life experiences are the chief influences in shaping people's views of knowledge, learning, and other aspects of life. Science, mathematics, and technology—in the context of schooling—can also play a key role in the process, for they are built upon a distinctive set of values, they reflect and respond to the values of society generally, and they are increasingly influential in shaping shared cultural values. Thus, to the degree that schooling concerns itself with values and attitudes—a matter of great sensitivity in a society that prizes cultural diversity and individuality and is wary of ideology—it must take scientific values and attitudes into account when preparing young people for life beyond school.

Similarly, there are certain thinking skills associated with science, mathematics, and technology that young people need to develop during their school years. These are mostly, but not exclusively, mathematical and logical skills that are essential tools for both formal and informal learning and for a lifetime of participation in society as a whole.

Taken together, these values, attitudes, and skills can be thought of as habits of mind because they all relate directly to a person's outlook on knowledge and learning and ways of thinking and acting.

This chapter presents recommendations about values, attitudes, and skills in the context of science education. The first part of the chapter focuses on four specific aspects of values and attitudes: the values inherent in science, mathematics, and technology; the social value of science and technology; the reinforcement of general social values; and people's attitudes toward their own ability to understand science and mathematics. The second part of the chapter focuses on skills related to computation and estimation, to manipulation and observation, to communication, and to critical response to arguments.

VALUES AND ATTITUDES

Science education should contribute to people's knowledge of the shared values of scientists, mathematicians, and engineers; reinforcement of general societal values; the inculcation in people of informed, balanced beliefs about the social value of science, mathematics, and technology; and the development in young people of positive attitudes toward learning science, mathematics, and technology.

Knowledge of the Values Inherent in Science, Mathematics, and Technology

Science, mathematics, and technology incorporate particular values, some of which are different in kind or intensity from those in other human enterprises, such as business, law, and the arts. To understand science, mathematics, and technology, it is essential to be aware of some of the values that underlie them and give them character and that are shared by the people who work in the three fields. These values are evident in the recommendations presented in this report's three chapters on the nature of science, mathematics, and technology, which consider the importance of the following verifiable data, testable hypotheses, and predictability in science; of rigorous proof and elegance in mathematics; and of optimum design in technology.

Reinforcement of General Societal Values

Culturally, science can be viewed as both revolutionary and conservative. The knowledge it generates sometimes forces us to change—even discard—beliefs we have long held about ourselves and our significance in the grand scheme of things. The revolutions that we associate with Newton, Darwin, and Lyell have had as much to do with our sense of humanity as they do with our knowledge of the earth and its inhabitants. Moreover, scientific knowledge can surprise us, even trouble us, especially when we discover that our world is not as we perceive it or would like it to be. The discovery that the earth is billions, rather than thousands, of years old may be a case in point. Such discoveries can be so distressing that it may take us years—or perhaps take society as a whole several generations—to come to terms with the new knowledge. Part of the price we pay for obtaining knowledge is that it may make us uncomfortable, at least initially. Becoming aware of the impact of scientific and technological developments on human beliefs and feelings should be part of everyone's science education.

It is also important for people to be aware that science is based upon everyday values even as it questions our understanding of the world and ourselves. Indeed, science is in many respects the systematic application of some highly regarded human values—integrity, diligence, fairness, curiosity, openness to new ideas, skepticism, and imagination. Scientists did not invent any of these values, and they are not the only people who hold them. But the broad field of science does incorporate and emphasize such values and dramatically demonstrates just how important they are for advancing human knowledge and welfare. Therefore, if science is taught effectively, the result will be to reinforce such generally desirable human attitudes and values.

Science education is in a particularly strong position to foster three of these attitudes and values—curiosity, openness to new ideas, and informed skepticism.

Curiosity

Scientists thrive on curiosity—and so do children. Children enter school alive with questions about everything in sight, and they differ from scientists only in not yet having learned how to go about finding answers and checking to see how good those answers are. Science education that fosters curiosity and teaches children how to channel that curiosity in productive ways serves both students and society well.

Openness to New Ideas

New ideas are essential for the growth of science—and for human activities in general. People with closed minds miss the joy of discovery and the satisfaction of intellectual growth throughout life. Because, as this report makes clear, the purpose of science education is not exclusively to produce scientists, it should help all students understand the great importance of carefully considering ideas that at first may seem disquieting to them or at odds with what they generally believe. The competition among ideas is a major source of tensions within science, between science and society, and within society. Science education should document the nature of such tensions from the history of science—and it should help students see the value to themselves and society of participating in the push and pull of conflicting ideas.

Informed Skepticism

Science is characterized as much by skepticism as by openness. Although a new theory may receive serious attention, it rarely gains widespread acceptance in science until its advocates can show that it is borne out by the evidence, is logically consistent with other principles that are not in question, explains more than its rival theories, and has the potential to lead to new knowledge. Because most scientists are skeptical about all new theories, such acceptance is usually a process of verification and refutation that can take years or even decades to run its course. Science education can help students to see the social value of systematic skepticism and to develop a healthy balance in their own minds between openness and skepticism.

The Social Value of Science, Mathematics, and Technology

There is another sense in which values come into play in thinking about the outcomes of the learning process. Quite apart from what scientific values students may adopt for themselves, there is the issue of what students should know and believe about the general social value of those endeavors. Is it necessary that every graduate be convinced of the great value to society of science, mathematics, and technology?

On balance, science, mathematics, and technology have advanced the quality of human existence, and students should become thoughtful supporters of them. But since science itself esteems independent thought so highly, it follows that teachers should not attempt to simply indoctrinate students into becoming uncritical supporters of science. Rather, they should take the position that in achieving the goals recommended in this report, students will end up with balanced views of the value of science, mathematics, and technology, and not be either uncritically positive or antagonistic.

Attitudes Toward Learning Science, Mathematics, and Technology

Students in elementary school have a spontaneous interest in nature and numbers. Nevertheless, many students emerge from school fearing mathematics and disdaining science as too dull and too hard to learn. They see science only as an academic activity, not as a way of understanding the world in which they live. The consequences of this aversion are severe, for it means that the lives of too many students are being limited and the nation's overall pool of talent from which scientists, mathematicians, and engineers are drawn is smaller than it should be.

The schools may not be able to turn this situation around by themselves, but they are essential to any realistic hope of doing so. It is within teachers' power to foster positive attitudes among their students. If they choose significant, accessible, and exciting topics in science and mathematics, if they feature teamwork as well as competition among students, if they focus on exploring and understanding more than the rote memorization of terms, and if they make sure all their students know they are expected to explore and learn and have their achievements acknowledged, then nearly all of those students will indeed learn. And in learning successfully, students will learn the most important lesson of all—namely, that they are able to do so.

COMPUTATION AND ESTIMATION

The recommendations presented in the preceding chapters are mostly about knowledge. However, they also imply that knowledge should be understood in ways that will enable it to be used in solving problems. In this sense, all of the foregoing recommendations are about thinking skills. Putting this the other way around, students are likely to learn thinking skills only in the process of coming to understand something substantive about the world, of encountering them in many different contexts and situations, and of using them repeatedly.

Computation

Repeated experience with computations in meaningful contexts will also foster the higher-level skill of judging when computations can most appropriately be made in one's head or on paper, or with the help of a calculator or computer. Each of these methods has a legitimate role in problem solving, although their roles may be different in different circumstances.

Basic Number Skills

In everyday life, one must be able to make simple calculations in one's mind. However, the actual amount of mental arithmetic needed is quite limited and is well within the ability of all normal individuals to learn. This skill requires, first of all, that the individual memorize and be able to recall immediately certain number facts:

- The sums, differences, and products of whole numbers from 1 to 10.
- The decimal equivalents of key common fractions—halves, thirds, two-thirds, fourths, three-fourths, fifths, tenths, and hundredths (but not sixths, sevenths, ninths, and other fractions rarely encountered by most people).
- The relation between decimal fractions and percentages (such as the equivalence of 0.23 and 23 percent).
- The relations among 10, 100, 1,000, 1 million, and 1 billion (for example, knowing that 1 million is a thousand thousands). Expressed as powers of 10, these relations are, successively, 10^1, 10^2, 10^3, 10^6, and 10^9.

There are two kinds of mental calculations that everyone ought to be able to perform:

- The addition of any two numbers that have two digits each.
- The multiplication and division of any number by 2, 10, and 100, to one or two significant digits.

Calculator Skills

In everyday life, and especially in the workplace, almost everyone encounters the need to make calculations. Until recently, paper and pencil were the most common means of solving problems that people could not do by mental arithmetic. For most students, school mathematics has meant doing calculations on paper. This usually takes the form of learning how to do long division, find percentages, or compute ratios, but not of learning why those algorithms work, when to use them, or how to make sense out of the answers.

The advent of the small, inexpensive electronic calculator has made it possible to change that situation radically. Because calculators are so fast, they can make available instructional time in school for doing and learning real mathematics. Students can readily learn how to figure out steps for solving ordinary numerical problems, which operations to use, and how to check the reasonableness of their answers. Universal numeracy becomes a real possibility.

The advantage of the calculator is not only pedagogical. Paper-and-pencil calculations are slow, prone to error, and as conceptually mysterious to most users as electronic tools are. When precision is desired, when the numbers being dealt with have multiple digits, or when the computation has several steps, the calculator offers many practical advantages over paper and pencil. But those advantages cannot be realized unless people learn how to use calculators intelligently. Calculator use does require skill, does not compensate for human errors of reasoning, often delivers answers with more precision than the data merit, and can be undermined by operator error. The key is for students to start using calculators early and to use them throughout the school years in as many different subjects as possible.

Everyone should be able to use a calculator to do the following:

- Add, subtract, multiply, and divide any two whole or decimal numbers (but not powers, roots, or trigonometric functions).
- Find the decimal equivalent of any fraction.
- Calculate what percentage one number is of another and take a percentage of any number (for example, 10 percent off, 60 percent gain).
- Find the reciprocal of any number.
- Determine rates from magnitudes (for example, speed from time and distance) and magnitudes from rates (for example, the amount of simple interest to be paid on the basis of knowing the interest rate and the principal, but not calculations using compound interest).
- Calculate circumferences and areas of rectangles, triangles, and circles, and the volumes of rectangular solids.
- Find the mean of a set of data.
- Determine by numerical substitution the value of simple algebraic expressions—for example, the expressions $aX+bY$, $a(A+B)$, and $(A-B)/(C+D)$.

- Convert compound units (such as yen per dollar into dollars per yen, miles per hour into feet per second).

To make full and effective use of calculators, everyone should also be able to do the following:

- Read and follow step-by-step instructions given in calculator manuals when learning new procedures.
- Make up and write out simple algorithms for solving problems that take several steps.
- Figure out what the unit (such as seconds, square inches, or dollars per tankful) of the answer will be from the inputs to the calculation. Most real-world calculations have to do with magnitudes (numbers associated with units), but ordinary calculators only respond with numbers. The user must be able to translate the calculator's "57," for example, into "57 miles per hour."
- Round off the number appearing in the calculator answer to a number of significant figures that is reasonably justified by those of the inputs. For example, for the speed of a car that goes 200 kilometers (give or take a kilometer or two) in 3 hours (give or take a minute or two), 67 kilometers per hour is probably accurate enough, 66.67 kilometers per hour is clearly going too far, and 66.666667 kilometers per hour is ridiculous.
- Judge whether an answer is reasonable by comparing it to an estimated answer. A result of 6.7 kilometers per hour or 667 kilometers per hour for the highway speed of an automobile, for example, should be rejected on sight.

Estimation

There are many circumstances in which an approximate answer is as useful as a precise one. Indeed, this may be the rule rather than the exception. Estimating approximate answers can often take the place of making a precise measurement or a careful calculation but in most cases will serve as a check of calculations made using electronic calculators or paper and pencil. Skill in estimation is based on a sense of what an adequate degree of precision is in a particular situation, which in turn depends on understanding the context of the problem and the purpose of the calculation. Among particular estimation skills, everyone should be able to estimate the following:

- Familiar lengths and weights, and also time periods.
- Distances and travel times from maps.
- The actual sizes of objects, based on the use of scale drawings.
- Probabilities of outcomes of familiar situations, either on the basis of history (such as the fact that a certain football team has won its opening game eight times in the last 10 years) or on the basis of the number of possible outcomes (for example, there are six sides on a die).

It often happens that an answer shown on a calculator is wrong because the information entered was wrong, the information was entered incorrectly, or the wrong sequence of operations was used. In situations where there is no basis for judging the appropriateness of an answer arrived at by calculation, everyone should be able to figure out a rough estimate of what the answer ought to be before accepting it. This involves being able to do three things:

- Carry out rough estimates of sums, differences, products, quotients, fractions, and percentages.
- Trace the source of any large disparity between the estimate and the calculated answer.
- Specify a magnitude only to the nearest power of 10. Thus, the population of the world is "on the order" of 10^9 (a billion) or 10^{10} (ten billion). Something that is improved by "an order of magnitude" changes by a factor of about 10—that is, anything from 4 or 5 times to 20 or 30 times larger (or smaller). A factor of 40 or a few hundred, for instance, would be more like two orders of magnitude.

MANIPULATION AND OBSERVATION

Everyone should acquire the ability to handle common materials and tools for dealing with household and other everyday technologies, for making careful observations, and for handling information. These include being able to do the following:

- Keep a notebook that accurately describes observations made, that carefully distinguishes actual observations from ideas and speculations about what was observed, and that is understandable weeks or months later.
- Store and retrieve computer information using topical, alphabetical, numerical, and key-word files, and use simple files of the individual's own devising.
- Enter and retrieve information on a computer, using standard software.
- Use appropriate instruments to make direct measurements of length, volume, weight, time interval, and temperature. Besides selecting the right instrument, this skill entails using a precision relevant to the situation (for example, measuring to the nearest quarter-inch is not good enough for making a cabinet, but is better than what is needed for building a long fence).
- Take readings from standard meter displays, both analog and digital, and make prescribed settings on dials, meters, and switches.
- Make electrical connections with various plugs and sockets and screw terminals, exercising reasonable safety.
- Shape, fasten, and unfasten common materials (such as wood, clay, paper, plastics, and metal) using ordinary hand and power tools, exercising reasonable safety.
- Dilute and mix dry and liquid materials (in the kitchen, garage, or laboratory) in prescribed proportions, exercising reasonable safety.
- Do simple troubleshooting on common mechanical and electrical systems, identifying and eliminating some possible causes of malfunction (such as a burned-out bulb versus an unplugged cord versus a faulty cord or switch in a house or an empty gas tank versus a run-down battery versus a flooded carburetor in an automobile).
- Compare consumer products on the basis of basic features, performance, durability, and cost, making supportable personal trade-offs.

- Look for the implications of changes in one part of a system—inputs, outputs, or connections—for the operation of other parts.

COMMUNICATION SKILLS

Discourse in science, mathematics, and technology calls for the ability to communicate ideas and share information with fidelity and clarity, and to read and listen with understanding. Some of the skills involved are specific to science, mathematics, and technology, and others are general—although even those are not independent of content. Everyone should have the skills that will enable him or her to do the following:

- Express orally and in writing the basic ideas covered by the recommendations in this report. This requires, above all, that students acquire some understanding of those ideas, build them into their own conceptual structures, and be able to illustrate them with examples and rational argument.
- Be comfortable and familiar with the standard vocabulary appropriate to the main ideas of science, mathematics, and technology, as used in this report. In many schools, science is taught solely as vocabulary, and that is largely what is tested. This approach is disastrous and is not what is called for here—which is a level of understanding of science that results in a useful vocabulary.
- Put correct interpretations on the terms "if..., then ...," "and," "every," "not," "correlates with," and "causes."
- Organize information into simple tables.
- Depict information and relationships by drawing freehand graphs to show trends (steady, accelerated, diminishing-return, and cyclic).
- Read values from pie charts and simple bar and line graphs, false-color maps, and two-way data tables, noting trends and extreme values and recognizing how the message in a graph is sensitive to the scale chosen.
- Check the correspondence between tabular, graphic, and verbal descriptions of data.
- Write and follow procedures in the form of step-by-step instructions, recipes, formulas, flow diagrams, and sketches.
- Comprehend and use basic geometrical relationships, including perpendicular, parallel, similar, congruent, tangent, rotation, and symmetry.
- Find and describe locations on maps, using rectangular and polar coordinates.
- Participate in group discussions on scientific topics by being able to restate or summarize what others have said, ask for clarification or elaboration, and take alternative perspectives.

CRITICAL-RESPONSE SKILLS

In various forms, the mass media, teachers, and peers inundate students with assertions and arguments, some of them in the realm of science, mathematics, and technology. Education should prepare people to read or listen to such assertions critically, deciding what evidence to pay attention to and what to dismiss, and distinguishing careful arguments from shoddy ones. Furthermore, people should be able to apply those same critical skills to their own observations, arguments, and conclusions, thereby becoming less bound by their own prejudices and rationalizations.

Although most people cannot be expected to become experts in technical fields, everyone can learn to detect the symptoms of doubtful assertions and arguments. These have to do with the ways in which purported results are reported. Students should learn to notice and be put on their guard by the following signs of weak arguments:

- The premises of the argument are not made explicit.
- The conclusions do not follow logically from the evidence given (for example, the truth of "Most rich people vote Republican" does not prove the truth of the converse, "Most people who vote Republican are rich").
- The argument is based on analogy but the comparison is not apt.
- Fact and opinion are intermingled, opinions are presented as facts, or it is not clear which is which.
- Celebrity is used as authority ("Film star endorses new diet").
- Vague attributions are used in place of specific references (for example, such common attributions as "leading doctors say ... ," "science has shown that ... ," "compared to some other states ... ," and "the scientific community recommends that ...").
- No mention is made, in self-reported opinions or information, of measures taken to guard against deliberate or subconscious distortion.
- No mention is made, in evidence said to come from an experiment, of control groups very much like the experimental group.
- Graphs are used that—by chopping off part of the scale, using unusual scale units, or using no scale at all—distort the appearance of results.
- It is implied that all members of a group—such as "teenagers," "consumers," "immigrants," or "patients"—have nearly identical characteristics that do not overlap those of other groups.
- Average results are reported, but not the amount of variation around the average.
- A percentage or fraction is given, but not the total sample size (as in "9 out of 10 dentists recommend ...").
- Absolute and proportional quantities are mixed (as in "3,400 more robberies in our city last year, whereas other cities had an increase of less than 1 percent").
- Results are reported with misleading preciseness (for example, representing 13 out of 19 students as 68.42 percent).
- Explanations or conclusions are represented as the only ones worth consideration, with no mention of other possibilities.