The American Association for the Advancement of Science is the leading general scientific society in the world, with more than 140,000 individual members and nearly 300 affiliated scientific, engineering, and mathematics societies and academies of science.

Project 2061 is a long-term initiative of the AAAS to reform K-12 education in natural and social science, mathematics, and technology. Begun in 1985, The Project is developing a set of tools to help local, state, and national educators redesign curriculum in these areas and ensure its success. *Science for All Americans,* outlines what all students should know and be able to do by the time they leave high school. Other publications of the Project address goals for progress at several grade levels along the way, principles for curriculum design, and changes needed in other aspects of the educational system to enable the curriculum to succeed. Each successive publication is based on the earlier ones and is meant to be used with them in planning reform. ■

SCIENCE

FOR ALL AMERICANS

PROJECT 2061

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

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This is the fifteenth Printing of ***Science for All Americans****, revised 1994.*
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This new edition of Science for All Americans is dedicated
to the memory of MARGARET MACVICAR, *who served ably as*
co-chair of the AAAS's National Council on Science and Technology Education.
This report owes much to her, as do all of us who had the great good fortune
to work with her in preparing it.

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BRIDGES TO THE FUTURE

PREFACE

Science for All Americans is the result of a three-year collaboration involving several hundred scientists, mathematicians, engineers, physicians, philosophers, historians, and educators. It is, we believe, as close as it is possible to come to a valid expression of the view of the science community on what constitutes literacy in science, mathematics, and technology. Our appreciation is expressed in the *Acknowledgement Section*, which includes the Preface to the first edition.

SFAA now has a companion report: ***Benchmarks for Science Literacy***. While the purpose of *SFAA* is to present a compelling vision of achievable learning goals, that of ***Benchmarks*** is to chart the territory that will have to be traveled to reach those goals. It does so by specifying what students should know and be able to do in science, mathematics, and technology at various grade levels.

Developing ***Benchmarks*** took four years and involved hundreds of educators and scientists. In the process, it became clear that some changes should be made in *SFAA,* and they were. As a result, this edition differs from its predecessor in the following ways:

> Some errors have been removed and some sentences have been revised to increase clarity. In no case did this result in a major change in the recommendations put forth.
>
> A few sections have been combined, moved, or renamed to match those in ***Benchmarks***. Most of these changes will be fairly obvious.
>
> The *Selected References Section* has been brought up to date by including notable reports that appeared after the publication of the first edition of *SFAA* in 1989.

Note that the last chapter is virtually unchanged. Some of the steps it called for have been taken, and some progress has been made, but what has not been done still needs doing.

Soon ***Science for All Americans***, together with ***Benchmarks*** will be followed by ***Blueprints for Reform*** and ***Designs for Science Literacy*** to help guide local, state, and national reform efforts.

F. JAMES RUTHERFORD
Director, Project 2061
American Association for the Advancement of Science

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* *The Council is appointed to oversee the work of Project 2061. The listing here is of the Council as it was constituted during the initial development of Science for All Americans, 1985 - 1989. (Affiliations given are those at the time of joining the Council.)*

■ INTRODUCTION

This book is about science literacy. *Science for All Americans* consists of a set of recommendations on what understandings and ways of thinking are essential for all citizens in a world shaped by science and technology. Below, we discuss briefly how these came about and describe their nature and organization. But first we take up the question of why such recommendations are needed.

THE NEED FOR SCIENCE LITERACY

Education has no higher purpose than preparing people to lead personally fulfilling and responsible lives. For its part, science education—meaning education in science, mathematics, and technology—should help students to develop the understandings and habits of mind they need to become compassionate human beings able to think for themselves and to face life head on. It should equip them also to participate thoughtfully with fellow citizens in building and protecting a society that is open, decent, and vital. America's future—its ability to create a truly just society, to sustain its economic vitality, and to remain secure in a world torn by hostilities—depends more than ever on the character and quality of the education that the nation provides for all of its children.

There is more at stake, however, than individual self-fulfillment and the immediate national interest of the United States. The most serious problems that humans now face are global: unchecked population growth in many parts of the world, acid rain, the shrinking of tropical rain forests and other great sources of species diversity, the pollution of the environment, disease, social strife, the extreme inequities in the distribution of the earth's wealth, the huge investment of human intellect and scarce resources in preparing for and conducting war, the ominous shadow of nuclear holocaust—the list is long, and it is alarming.

What the future holds in store for individual human beings, the nation, and the world depends largely on the wisdom with which

COMET HALLEY, *photographed from Las Campanas Observatory, Chile, March 1986.*

humans use science and technology. And that, in turn, depends on the character, distribution, and effectiveness of the education that people receive. Briefly put, the national council's argument is this:

> Science, energetically pursued, can provide humanity with the knowledge of the biophysical environment and of social behavior needed to develop effective solutions to its global and local problems; without that knowledge, progress toward a safe world will be unnecessarily handicapped.
>
> By emphasizing and explaining the dependency of living things on each other and on the physical environment, science fosters the kind of intelligent respect for nature that should inform decisions on the uses of technology; without that respect, we are in danger of recklessly destroying our life-support system.
>
> Scientific habits of mind can help people in every walk of life to deal sensibly with problems that often involve evidence, quantitative considerations, logical arguments, and uncertainty; without the ability to think critically and independently, citizens are easy prey to dogmatists, flimflam artists, and purveyors of simple solutions to complex problems.
>
> Technological principles relating to such topics as the nature of systems, the importance of feedback and control, the cost-benefit-risk relationship, and the inevitability of side effects give people a sound basis for assessing the use of new technologies and their implications for the environment and culture; without an understanding of those principles, people are unlikely to move beyond consideration of their own immediate self-interest.
>
> Although many pressing global and local problems have technological origins, technology provides the tools for dealing with such problems, and the instruments for generating, through science, crucial new knowledge. Without the continuous development and creative use of new technologies, society may limit its capacity for survival and for working toward a world in which the human species is at peace with itself and its environment.
>
> The life-enhancing potential of science and technology cannot be realized unless the public in general comes to understand science, mathematics, and technology and to acquire scientific habits of mind. Without a science- literate population, the outlook for a better world is not promising.

Most Americans are not science-literate. One only has to look at the international studies of educational performance to see that U.S. students rank near the bottom in science and mathematics—hardly what one would expect if the schools were doing their job well. The most recent international mathematics study has reported, for instance, that U.S. students are well below the international level in problem solving, and the latest study of National Assessment of Educational Progress has found that despite some small recent gains, the average performance of 17-year-olds in 1986 remained substantially lower than it had been in 1969.

The United States should be able to do better. It is, after all, a prosperous nation that claims to value public education as the foundation of democracy. And it has deliberately staked its future well-being on its competence—even leadership—in science and technology. Surely it is reasonable, therefore, to expect this commitment to show up in the form of a modern, well-supported school system staffed by highly qualified teachers and administrators. And surely the curriculum in such schools should feature science, mathematics, and technology for all students. In fact, however, the situation existing in far too many states and school districts is quite different:

> Few elementary school teachers have even a rudimentary education in science and mathematics, and many junior and senior high school teachers of science and mathematics do not meet reasonable standards of preparation in those fields. Unfortunately, such deficiencies have long been tolerated by the institutions that prepare teachers, the public bodies that license them, the schools that hire them and give them their assignments, and even the teaching profession itself.
>
> Teachers of science and mathematics have crushing teaching loads that make it nearly impossible for them to perform well, no matter how excellent their preparation may have been. This burden is made worse by the almost complete absence of a modern support system to back them up. As the world approaches the twenty-first

century, the schools of America—when it comes to the deployment of people, time, and technology—seem to be still stuck in the nineteenth century.

The present science textbooks and methods of instruction, far from helping, often actually impede progress toward science literacy. They emphasize the learning of answers more than the exploration of questions, memory at the expense of critical thought, bits and pieces of information instead of understandings in context, recitation over argument, reading in lieu of doing. They fail to encourage students to work together, to share ideas and information freely with each other, or to use modern instruments to extend their intellectual capabilities.

The present curricula in science and mathematics are overstuffed and undernourished. Over the decades, they have grown with little restraint, thereby overwhelming teachers and students and making it difficult for them to keep track of what science, mathematics, and technology is truly essential. Some topics are taught over and over again in needless detail; some that are of equal or greater importance to science literacy—often from the physical and social sciences and from technology—are absent from the curriculum or are reserved for only a few students.

To turn this situation around will take determination, resources, leadership, and time. The world has changed in such a way that science literacy has become necessary for everyone, not just a privileged few; science education will have to change to make that possible. We are all responsible for the current deplorable state of affairs in education, and it will take all of us to reform it. Project 2061 hopes to contribute to that national effort.

RECOMMENDATIONS

One fundamental premise of Project 2061 is that the schools do not need to be asked to teach more and more content, but rather to focus on what is essential to science literacy and to teach it more effectively. Accordingly, the national council's recommendations for a common core of learning are limited to the ideas and skills having the greatest scientific and educational significance for science literacy.

Science for All Americans is based on the belief that the science-literate person is one who is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations; understands key concepts and principles of science; is familiar with the natural world and recognizes both its diversity and unity; and uses scientific knowledge and scientific ways of thinking for individual and social purposes. The recommendations are presented in 12 chapters that thematically cover four major categories:

- Chapters 1 through 3 deal with the nature of science, mathematics, and technology—collectively, the scientific endeavor—as human enterprises.
- Chapters 4 through 9 cover basic knowledge about the world as currently seen from the perspective of science and mathematics and as shaped by technology.
- Chapters 10 and 11 present what people should understand about some of the great episodes in the history of the scientific endeavor and about some crosscutting themes that can serve as tools for thinking about how the world works.
- Chapter 12 lays out the habits of mind that are essential for science literacy.

In considering these recommendations, it is important to keep in mind some of the special features of the report:

The Recommendations Reflect a Broad Definition of Science Literacy

Science literacy—which encompasses mathematics and technology as well as the natural and social sciences—has many facets. These include being familiar with the natural world and respecting its unity; being aware of some of the important ways in which mathematics, technology, and the sciences depend upon one another; understanding some of the key concepts and principles of science; having a capacity for scientific ways of thinking; knowing that science, mathematics, and technology are human enterprises, and knowing what that implies about their strengths and limitations; and being able to use scientific knowledge and ways of thinking for personal and social purposes.

Some of these facets of science literacy are addressed only in specific places in the report, whereas others are woven into the text of the chapters. It is essential, therefore, that the recommendations be viewed in their entirety as a multifaceted discussion of science literacy.

The Recommendations in This Report Apply to All Students

The set of recommendations constitutes a common core of learning in science, mathematics, and technology for all young people, regardless of their social circumstances and career aspirations. In particular, the recommendations pertain to those who in the past have largely been bypassed in science and mathematics education: ethnic and language minorities and girls. The recommendations do not include every interesting topic that was suggested and do not derive from diluting the traditional college preparatory curriculum. Nevertheless, the recommendations are deliberately ambitious, for it would be worse to underestimate what students can learn than to expect too much. The national council is convinced that—given clear goals, the right resources, and good teaching throughout 13 years of school—essentially all students (operationally meaning 90 percent or more) will be able to reach all of the recommended learning goals (meaning at least 90 percent) by the time they graduate from high school.

At the same time, however, no student should be limited to the common core of learning spelled out in this report. In response to special interests and skills, some students will want to gain a more sophisticated understanding of the topics than what is suggested here, and some will want to pursue topics not included here at all. A well-designed curriculum will be able to serve those special needs without sacrificing a commitment to a common core of learning in science, mathematics, and technology.

The Recommendations Have Been Selected on the Basis of Both Scientific and Human Significance

The schools do not need to be asked to teach more and more content, but to teach less in order to teach it better. By concentrating on fewer topics, teachers can introduce ideas gradually, in a variety of contexts, reinforcing and extending them as students mature. Students will end up with richer insights and deeper understandings than they could hope to gain from a superficial exposure to more topics than they can assimilate. The problem for curriculum developers, therefore, is much less what to add than what to eliminate.

Reversing the accretion of material over scores of years is thus a major goal of Project 2061. But addressing this goal has meant making choices. The criteria for identifying a common core of learning in science, mathematics, and technology were both scientific and educational. Consideration was given first to the ideas that seemed to be of unusual scientific importance, because there is simply too much knowledge for anyone to acquire in a lifetime, let alone 13 years. This meant favoring content that has had great influence on what is worth knowing now and what will still be worth knowing decades hence, and ruling out topics mainly of only passing technical interest or limited scientific scope. In particular, concepts were chosen that could serve as a lasting foundation on which to build more knowledge over a lifetime. The choices then had to meet important criteria having to do with human life and with the broad goals that justify universal public education in a free society. The criteria were:

Utility. Will the proposed content—knowledge or skills—significantly enhance the graduate's long-term employment prospects? Will it be useful in making personal decisions?

Social Responsibility. Is the proposed content likely to help citizens participate intelligently in making social and political decisions on matters involving science and technology?

The Intrinsic Value of Knowledge. Does the proposed content present aspects of science, mathematics, and technology that are so important in human history or so pervasive in our culture that a general education would be incomplete without them?

Philosophical Value. Does the proposed content contribute to the ability of people to ponder the enduring questions of human meaning such as life and death, perception and reality, the individual good versus the collective welfare, certainty and doubt?

Childhood Enrichment. Will the proposed content enhance childhood (a time of life that is important in its own right and not solely for what it may lead to in later life)?

The Recommendations Are Neither All New Nor Intended to Be Fixed for All Time

In formulating recommendations, no attempt was made to either seek novelty or avoid it. The task was to identify a minimal core of critical understandings and skills, whether or not they happen to be part of current school curricula. The recommendations do not constitute the only possible ones, and indeed there were differences among the participants in this project on various topics. The national council does believe, however, that the recommendations make good sense and that they offer a sound basis for designing curricula in science, mathematics, and technology.

But science, mathematics, and technology are continually in flux—holding onto some ideas and ways of doing things, reshaping or discarding some, adding others. The time will inevitably come—sooner in some areas than others—when the recommendations will need to be revised to accommodate new knowledge. Furthermore, as educators and scientists work together in Phase II of Project 2061 to design curriculum models based on this report, they are likely to reach their own conclusions on the appropriateness of these recommendations and to suggest changes. In any case, the recommendations are not presented to set up a new and unalterable orthodoxy, but rather to provide a credible resource for the Phase II development, to provoke lively debate on the question of the content of education, and to catalyze curriculum reform.

This Report Is Not a Curriculum Document or a Textbook

The reader should not expect to find recommendations in this report on what should be taught in any particular course or at any grade level. The report deals only with learning goals—what students should remember, understand, and be able to do after they have left school as a residue of their total school experience—and not with how to organize the curriculum to achieve them. Neither is the presentation of recommendations meant to instruct the reader as a text does. No linear presentation of topics can satisfactorily represent the connectedness of ideas and experiences that would be essential in an actual curriculum or textbook.

The Recommendations Are Intended to Convey the Levels of Understanding Appropriate for All People

For most educational purposes, broad generalizations (such as 'everyone should know how science and technology are related') are no more useful than are long lists of specific topics (atoms, cells, planets, graphs, etc.). Neither approach reveals what is to be learned, and both require the reader to guess what level of sophistication is intended. Thus, the specific recommendations in this report are framed in enough detail to convey the levels of understanding and the contexts of understanding intended. The recommendations have been formulated under four levels of generalization:

Chapters. Each chapter deals with a major set of related topics. Collectively, the chapter titles lay out a conceptual framework for understanding science that people can use throughout their lives as they gain new knowledge about the world.

Headings. Within each chapter, headings such as Forces That Shape the Earth or Interdependence of Life identify the conceptual categories that all students should be familiar with. A list of all the headings would provide an approximate answer to the question of the scope, but not the content, of the specific recommendations.

Paragraphs. Under each heading are paragraphs that express the residual knowledge, insights, and skills that people should possess after the details have faded from memory. If high school graduates were interviewed about a topic—Information Processing, say—they should be able to come up, in their own words, with the ideas sketched in the paragraphs under that heading.

Vocabulary. The language of the recommendations is intended to convey the level of learning advocated. The recommendations are written for today's educated adults, not students—but the technical vocabulary is limited to what would be desirable for all students to command, as a minimum, by the time they finish school. This vocabulary should be viewed as a product of a sound education in science, mathematics, and technology, but not its main purpose.

In sum, the recommendations are—to different degrees of specificity—implicit in the titles, headings, text, and vocabulary of the 12 chapters that follow. Yet there is no way, in so short a document, to convey the quality of knowledge envisaged across the full range of topics. This quality—the way in which something is known—depends largely on how it is learned. In this regard, the discussion of learning and teaching in Part III provides a perspective for understanding the nature of the recommendations themselves.

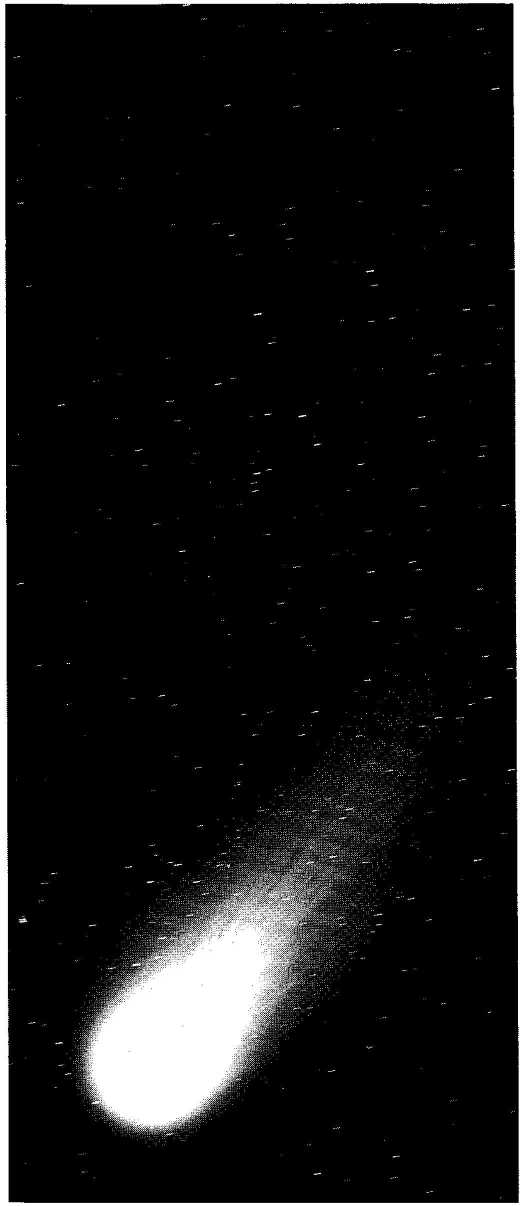
THE SOURCE OF THE RECOMMENDATIONS

The recommendations in *Science for All Americans* are not those of a single person, nor are they those of a committee. They emerged, instead, from a lengthy process designed to capture both the daring insights of the individual and the critical confrontation of the group. Briefly, the steps were these:

> Scientific panels appointed by the American Association for the Advancement of Science were charged with coming up with recommendations in five domains: the biological and health sciences; mathematics; the physical and information sciences and engineering; the social and behavioral sciences; and, technology. Each panel met frequently over a two-year period, often inviting consultants to meet with them to present ideas and to participate in the discussion of particular suggestions being put forward by one or more panel members.
>
> To gain consideration, individual panel members had to defend their propositions in terms of both scientific and educational significance. As the number that survived this critical test grew, another condition was added: what should be stricken from the list to make room for the new candidate? From time to time, the panels had an opportunity to study and criticize one another's tentative recommendations. At the conclusion of its deliberations, each panel submitted a report to the National Council on Science and Technology Education summarizing its conclusions. The reports were then published by the AAAS.

> The national council was also appointed by the AAAS. Its responsibility was to provide quality control for and guidance to the panels and the project staff. (This undertaking is part of a larger one called Project 2061: Education for a Changing Future, which is briefly described in Chapter 15.) The staff—primarily Rutherford and Ahlgren—met regularly with the panels and by mutual agreement took on the responsibility of drafting copy covering the territory common to all of the panels, such as the nature of the scientific endeavor, history, and cross-cutting themes. Panel members submitted ideas and criticized successive drafts.
>
> Then the staff, with the help of many experts, undertook to prepare a single cogent report drawing on the panel reports and its own work, but not simply synthesizing them. Drafts were written, submitted to the national council, debated, and then rewritten. When the national council was finally satisfied, the draft was reviewed in detail by 130 highly qualified persons, their comments studied, and a final draft prepared. The national council recommended Science for All Americans, as it had finally come to be known, to the AAAS Board of Directors. Board members read the entire document, listened to the arguments in its favor by the national council co-chairs, discussed it at length, then voted unanimously to authorize publication.

So *Science for All Americans* represents the informed thinking of the science, mathematics, and technology communities as nearly as such a thing can be ascertained. It is a consensus, to be sure, but not a superficial one of the kind that would result from, say, a survey or a conference. The process cannot be said to have led to the only plausible set of recommendations on the education in science, mathematics, and technology for all children, but it certainly yielded recommendations in which we can have confidence. It is an ambitious but attainable vision that emphasizes meanings, connections, and contexts rather than fragmented bits and pieces of information and favors quality of understanding over quantity of coverage. Is not that precisely the kind of education that we should want for all Americans? ■



Among the eucalyptus trees,
Green leaves dancing in the autumn wind,
The cold pale watcher of mankind
Treads his ancient trail again.

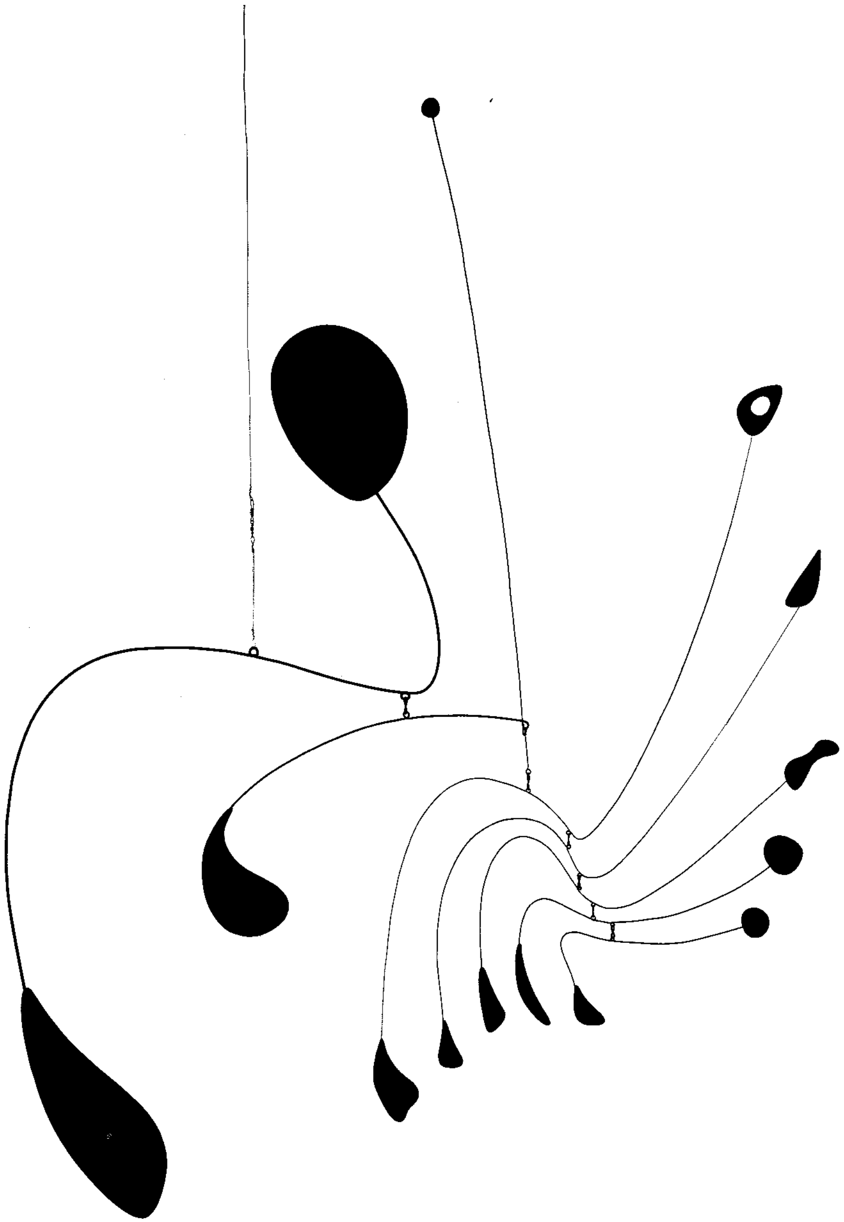
Pass swiftly by the angry bull,
The starry fish and water jar,
Defy the Sun's consuming flame,
The archer's bow,
The scorpion's sting,
The centaur's wrath,
The deadly coil of the hydra–
But then be gone.
Ask not for Harold of Hastings,
You know he is not here;
Nor Attila, vanquished at Chalons,
Edmund, master of Isaac's rules.
Nor Giotto, and the Zealots of Jerusalem.

You must have seen
The ships that rose to greet you.
Next time there will be more.
They'll even mount your haggard head
And ride you into Neptune's night!
Yes, we still are bold.
Though once more we now learn
The message that you bear,
Resonate to your grim tattoo,
The gravest rhythm of our race,
Yet wait with hope your sure return.

GEORGE W. WETHERILL

George W. Wetherill, the director of the Carnegie Institution of Washington's Department for Terrestrial Magnetism, wrote the above lines when he was in La Serena, Chile, in April 1986 to observe Comet Halley. Photograph by **Alan Dressler**, from the Las Campanas Observatory, Chile, March 1986.

RECOMMENDATIONS FOR SCIENCE LITERACY



ALEXANDER CALDER, *Hanging Spider, 1940.*

CHAPTER 1

THE NATURE OF SCIENCE

Over the course of human history, people have developed many interconnected and validated ideas about the physical, biological, psychological, and social worlds. Those ideas have enabled successive generations to achieve an increasingly comprehensive and reliable understanding of the human species and its environment. The means used to develop these ideas are particular ways of observing, thinking, experimenting, and validating. These ways represent a fundamental aspect of the nature of science and reflect how science tends to differ from other modes of knowing.

It is the union of science, mathematics, and technology that forms the scientific endeavor and that makes it so successful. Although each of these human enterprises has a character and history of its own, each is dependent on and reinforces the others. Accordingly, the first three chapters of recommendations draw portraits of science, mathematics, and technology that emphasize their roles in the scientific endeavor and reveal some of the similarities and connections among them.

This chapter lays out recommendations for what knowledge of the way science works is requisite for scientific literacy. The chapter focuses on three principal subjects: the scientific world view, scientific methods of inquiry, and the nature of the scientific enterprise. Chapters 2 and 3 consider ways in which mathematics and technology differ from science in general. Chapters 4 through 9 present views of the world as depicted by current science; Chapter 10, HISTORICAL PERSPECTIVES, covers key episodes in the development of science; and Chapter 11, COMMON THEMES, pulls together ideas that cut across all these views of the world.

RECOMMENDATIONS

THE SCIENTIFIC WORLD VIEW

Scientists share certain basic beliefs and attitudes about what they do and how they view their work. These have to do with the nature of the world and what can be learned about it.

The World Is Understandable

Science presumes that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic study. Scientists believe that through the use of the intellect, and with the aid of instruments that extend the senses, people can discover patterns in all of nature.

Science also assumes that the universe is, as its name implies, a vast single system in which the basic rules are everywhere the same. Knowledge gained from studying one part of the universe is applicable to other parts. For instance, the same principles of motion and gravitation that explain the motion of falling objects on the surface of the earth also explain the motion of the moon and the planets. With some modifications over the years, the same principles of motion have applied to other forces—and to the motion of everything, from the smallest nuclear particles to the most massive stars, from sailboats to space vehicles, from bullets to light rays.

Scientific Ideas Are Subject to Change

Science is a process for producing knowledge. The process depends both on making careful observations of phenomena and on inventing theories for making sense out of those observations. Change in knowledge is inevitable because new observations may challenge prevailing theories. No matter how well one theory explains a set of observations, it is possible that another theory may fit just as well or better, or may fit a still wider range of observations. In science, the testing and improving and occasional discarding of theories, whether new or old, go on all the time. Scientists assume that even if there is no way to secure complete and absolute truth, increasingly accurate approximations can be made to account for the world and how it works.

Scientific Knowledge Is Durable

Although scientists reject the notion of attaining absolute truth and accept some uncertainty as part of nature, most scientific knowledge is durable. The modification of ideas, rather than their outright rejection, is the norm in science, as powerful constructs tend to survive and grow more precise and to become widely accepted. For example, in formulating the theory of relativity, Albert Einstein did not discard the Newtonian laws of motion but rather showed them to be only an approximation of limited application within a more general concept. (The National Aeronautics and Space Administration uses Newtonian mechanics, for instance, in calculating satellite trajectories.) Moreover, the growing ability of scientists to make accurate predictions about natural phenomena provides convincing evidence that we really are gaining in our understanding of how the world works. Continuity and stability are as characteristic of science as change is, and confidence is as prevalent as tentativeness.

Science Cannot Provide Complete Answers to All Questions

There are many matters that cannot usefully be examined in a scientific way. There are, for instance, beliefs that—by their very nature—cannot be proved or disproved (such as the existence of supernatural powers and beings, or the true purposes of life). In other cases, a scientific approach that may be valid is likely to be rejected as irrelevant by people who hold to certain beliefs (such as in miracles, fortune-telling, astrology, and superstition). Nor do scientists have the means to settle issues concerning good and evil, although they can sometimes contribute to the discussion of such issues by identifying the likely consequences of particular actions, which may be helpful in weighing alternatives.

SCIENTIFIC INQUIRY

Fundamentally, the various scientific disciplines are alike in their reliance on evidence, the use of hypothesis and theories, the kinds of logic used, and much more. Nevertheless, scientists differ greatly from one another in what phenomena they investigate and in how they go about their work; in the reliance they place on historical data or on experimental findings and on qualitative or quantitative methods; in their recourse to fundamental principles; and in how much they draw on the findings of other sciences. Still, the exchange of techniques, information, and concepts goes on all the time among scientists, and there are common understandings among them about what constitutes an investigation that is scientifically valid.

Scientific inquiry is not easily described apart from the context of particular investigations. There simply is no fixed set of steps that scientists always follow, no one path that leads them unerringly to scientific knowledge. There are, however, certain features of science that give it a distinctive character as a mode of inquiry. Although those features are especially characteristic of the work of professional scientists, everyone can exercise them in thinking scientifically about many matters of interest in everyday life.

Science Demands Evidence

Sooner or later, the validity of scientific claims is settled by referring to observations of phenomena. Hence, scientists concentrate on getting accurate data. Such evidence is obtained by observations and measurements taken in situations that range from natural settings (such as a forest) to completely contrived ones (such as the laboratory). To make their observations, scientists use their own senses, instruments (such as microscopes) that enhance those senses, and instruments that tap characteristics quite different from what humans can sense (such as magnetic fields). Scientists observe passively (earthquakes, bird migrations), make collections (rocks, shells), and actively probe the world (as by boring into the earth's crust or administering experimental medicines).

In some circumstances, scientists can control conditions deliberately and precisely to obtain their evidence. They may, for example, control the temperature, change the concentration of chemicals, or choose which organisms mate with which others. By varying just one condition at a time, they can hope to identify its exclusive effects on what happens, uncomplicated by changes in other conditions. Often, however, control of conditions may be impractical (as in studying stars), or unethical (as in studying people), or likely to distort the natural phenomena (as in studying wild animals in captivity). In such cases, observations have to be made over a sufficiently wide range of naturally occurring conditions to infer what the influence of various factors might be. Because of this reliance on evidence, great value is placed on the development of better instruments and techniques of observation, and the findings of any one investigator or group are usually checked by others.

Science Is a Blend of Logic and Imagination

Although all sorts of imagination and thought may be used in coming up with hypotheses and theories, sooner or later scientific arguments must conform to the principles of logical reasoning—that is, to testing the validity of arguments by applying certain criteria of inference, demonstration, and common sense. Scientists may often disagree about the value of a particular piece of evidence, or about the appropriateness of particular assumptions that are made—and therefore disagree about what conclusions are justified. But they tend to agree about the principles of logical reasoning that connect evidence and assumptions with conclusions.

Scientists do not work only with data and well-developed theories. Often, they have only tentative hypotheses about the way things may be. Such hypotheses are widely used in science for choosing what data to pay attention to and what additional data to seek, and for guiding the interpretation of data. In fact, the process of formulating and testing hypotheses is one of the core activities of scientists. To be useful, a hypothesis should suggest what evidence would support it and what evidence would refute it. A hypothesis that cannot in principle be put to the test of evidence may be interesting, but it is not likely to be scientifically useful.

The use of logic and the close examination of evidence are necessary but not usually sufficient for the advancement of science. Scientific concepts do not emerge automatically from data or from any amount of analysis alone. Inventing hypotheses or theories to imagine how the world works and then figuring out how they can be put to the test of reality is as creative as writing poetry, composing music, or designing skyscrapers. Sometimes discoveries in science are made unexpectedly, even by accident. But knowledge and creative insight are usually required to recognize the meaning of the unexpected. Aspects of data that have been ignored by one scientist may lead to new discoveries by another.

Science Explains and Predicts

Scientists strive to make sense of observations of phenomena by constructing explanations for them that use, or are consistent with, currently accepted scientific principles. Such explanations—theories—may be either sweeping or restricted, but they must be logically sound and incorporate a significant body of scientifically valid observations. The credibility of scientific theories often comes from their ability to show relationships among phenomena that previously seemed unrelated. The theory of moving continents, for example, has grown in credibility as it has shown relationships among such diverse phenomena as earthquakes, volcanoes, the match between types of fossils on different continents, the shapes of continents, and the contours of the ocean floors.

The essence of science is validation by observation. But it is not enough for scientific theories to fit only the observations that are already known. Theories should also fit additional observations that were not used in formulating the theories in the first place; that is, theories should have predictive power. Demonstrating the predictive power of a theory does not necessarily require the prediction of events in the future. The predictions may be about evidence from the past that has not yet been found or studied. A theory about the origins of human beings, for example, can be tested by new discoveries of human-like fossil remains. This approach is clearly necessary for reconstructing the events in the history of the earth or of the life forms on it. It is also necessary for the study of processes that usually occur very slowly, such as the building of mountains or the aging of stars. Stars, for example, evolve more slowly than we can usually observe. Theories of the evolution of stars, however, may predict unsuspected relationships between features of starlight that can then be sought in existing collections of data about stars.

Scientists Try to Identify and Avoid Bias

When faced with a claim that something is true, scientists respond by asking what evidence supports it. But scientific evidence can be biased in how the data are interpreted, in the recording or reporting of the data, or even in the choice of what data to consider in the first place. Scientists' nationality, sex, ethnic origin, age, political convictions, and so on may incline them to look for or emphasize one or another kind of evidence or interpretation. For example, for many years the study of primates—by male scientists—focused on the competitive social behavior of males. Not until female scientists entered the field was the importance of female primates' community-building behavior recognized.

Bias attributable to the investigator, the sample, the method, or the instrument may not be completely avoidable in every instance, but scientists want to know the possible sources of bias and how bias is likely to influence evidence. Scientists want, and are expected, to be as alert to possible bias in their own work as in that of other scientists, although such objectivity is not always achieved. One safeguard against undetected bias in an area of study is to have many different investigators or groups of investigators working in it.

Science Is Not Authoritarian

It is appropriate in science, as elsewhere, to turn to knowledgeable sources of information and opinion, usually people who specialize in relevant disciplines. But esteemed authorities have been wrong many times in the history of science. In the long run, no scientist, however famous or highly placed, is empowered to decide for other scientists what is true, for none are believed by other scientists to have special access to the truth. There are no preestablished conclusions that scientists must reach on the basis of their investigations.

In the short run, new ideas that do not mesh well with mainstream ideas may encounter vigorous criticism, and scientists investigating such ideas may have difficulty obtaining support for their research. Indeed, challenges to new ideas are the legitimate business of science in building valid knowledge. Even the most prestigious scientists have occasionally refused to accept new theories despite there being enough accumulated evidence to convince others. In the long run, however, theories are judged by their results: When someone comes up with a new or improved version that explains more phenomena or answers more important questions than the previous version, the new one eventually takes its place.

THE SCIENTIFIC ENTERPRISE

Science as an enterprise has individual, social, and institutional dimensions. Scientific activity is one of the main features of the contemporary world and, perhaps more than any other, distinguishes our times from earlier centuries.

Science Is a Complex Social Activity

Scientific work involves many individuals doing many different kinds of work and goes on to some degree in all nations of the world. Men and women of all ethnic and national backgrounds participate in science and its applications. These people—scientists and engineers, mathematicians, physicians, technicians, computer programmers, librarians, and others—may focus on scientific knowledge either for its own sake or for a particular practical purpose, and they may be concerned with data gathering, theory building, instrument building, or communicating.

As a social activity, science inevitably reflects social values and viewpoints. The history of economic theory, for example, has paralleled the development of ideas of social justice—at one time, economists considered the optimum wage for workers to be no more than what would just barely allow the workers to survive. Before the twentieth century, and well into it, women and people of color were essentially excluded from most of science by restrictions on their education and employment opportunities; the remarkable few who overcame those obstacles were even then likely to have their work belittled by the science establishment.

The direction of scientific research is affected by informal influences within the culture of science itself, such as prevailing opinion on what questions are most interesting or what methods of investigation are most likely to be fruitful. Elaborate processes involving scientists themselves have been developed to decide which research proposals receive funding, and committees of scientists regularly review progress in various disciplines to recommend general priorities for funding.

Science goes on in many different settings. Scientists are employed by universities, hospitals, business and industry, government, independent research organizations, and scientific associations. They may work alone, in small groups, or as members of large research teams. Their places of work include classrooms, offices, laboratories, and natural field settings from space to the bottom of the sea.

Because of the social nature of science, the dissemination of scientific information is crucial to its progress. Some scientists present their findings and theories in papers that are delivered at meetings or published in scientific journals. Those papers enable scientists to inform others about their work, to expose their ideas to criticism by other scientists, and, of course, to stay abreast of scientific developments around the world. The advancement of information science (knowledge of the nature of information and its manipulation) and the development of information technologies (especially computer systems) affect all sciences. Those technologies speed up data collection, compilation, and analysis; make new kinds of analysis practical; and shorten the time between discovery and application.

Science Is Organized into Content Disciplines and Is Conducted in Various Institutions

Organizationally, science can be thought of as the collection of all of the different scientific fields, or content disciplines. From anthropology through zoology, there are dozens of such disciplines. They differ from one another in many ways, including history, phenomena studied, techniques and language used, and kinds of outcomes desired. With respect to purpose and philosophy, however, all are equally scientific and together make up the same scientific endeavor. The advantage of having disciplines is that they provide a conceptual structure for organizing research and research findings. The disadvantage is that their divisions do not necessarily match the way the world works, and they can make communication difficult. In any case, scientific disciplines do not have fixed borders. Physics shades into chemistry, astronomy, and geology, as does chemistry into biology and psychology, and so on. New scientific disciplines (astrophysics and sociobiology, for instance) are continually being formed at the boundaries of others. Some disciplines grow and break into subdisciplines, which then become disciplines in their own right.

Universities, industry, and government are also part of the structure of the scientific endeavor. University research usually emphasizes knowledge for its own sake, although much of it is also directed toward practical problems. Universities, of course, are also particularly committed to educating successive generations of scientists, mathematicians, and engineers. Industries and businesses usually emphasize research directed to practical ends, but many also sponsor research that has no immediately obvious applications, partly on the premise that it will be applied fruitfully in the long run. The federal government funds much of the research in universities and in industry but also supports and conducts research in its many national laboratories and research centers. Private foundations, public-interest groups, and state governments also support research.

Funding agencies influence the direction of science by virtue of the decisions they make on which research to support. Other deliberate controls on science result from federal (and sometimes local) government regulations on research practices that are deemed to be dangerous and on the treatment of the human and animal subjects used in experiments.

There Are Generally Accepted Ethical Principles in the Conduct of Science

Most scientists conduct themselves according to the ethical norms of science. The strongly held traditions of accurate recordkeeping, openness, and replication, buttressed by the critical review of one's work by peers, serve to keep the vast majority of scientists well within the bounds of ethical professional behavior. Sometimes, however, the pressure to get credit for being the first to publish an idea or observation leads some scientists to withhold information or even to falsify their findings. Such a violation of the very nature of science impedes science. When discovered, it is strongly condemned by the scientific community and the agencies that fund research.

Another domain of scientific ethics relates to possible harm that could result from scientific experiments. One aspect is the treatment of live experimental subjects. Modern scientific ethics require that due regard must be given to the health, comfort, and well-being of animal subjects. Moreover, research involving human subjects may be conducted only with the informed consent of the subjects, even if this constraint limits some kinds of potentially important research or influences the results. Informed consent entails full disclosure of the risks and intended benefits of the research and the right to refuse to participate. In addition, scientists must not knowingly subject coworkers, students, the neighborhood, or the community to health or property risks without their knowledge and consent.

The ethics of science also relates to the possible harmful effects of applying the results of research. The long-term effects of science may be unpredictable, but some idea of what applications are expected from scientific work can be ascertained by knowing who is interested in funding it. If, for example, the Department of Defense offers contracts for working on a line of theoretical mathematics, mathematicians may infer that it has application to new military technology and therefore would likely be subject to secrecy measures. Military or industrial secrecy is acceptable to some scientists but not to others. Whether a scientist chooses to work on research of great potential risk to humanity, such as nuclear weapons or germ warfare, is considered by many scientists to be a matter of personal ethics, not one of professional ethics.

Scientists Participate in Public Affairs Both as Specialists and as Citizens

Scientists can bring information, insights, and analytical skills to bear on matters of public concern. Often they can help the public and its representatives to understand the likely causes of events (such as natural and technological disasters) and to estimate the possible effects of projected policies (such as ecological effects of various farming methods). Often they can testify to what is not possible. In playing this advisory role, scientists are expected to be especially careful in trying to distinguish fact from interpretation, and research findings from speculation and opinion; that is, they are expected to make full use of the principles of scientific inquiry.

Even so, scientists can seldom bring definitive answers to matters of public debate. Some issues are too complex to fit within the current scope of science, or there may be little reliable information available, or the values involved may lie outside of science. Moreover, although there may be at any one time a broad consensus on the bulk of scientific knowledge, the agreement does not extend to all scientific issues, let alone to all science-related social issues. And of course, on issues outside of their expertise, the opinions of scientists should enjoy no special credibility.

In their work, scientists go to great lengths to avoid bias—their own as well as that of others. But in matters of public interest, scientists, like other people, can be expected to be biased where their own personal, corporate, institutional, or community interests are at stake. For example, because of their commitment to science, many scientists may understandably be less than objective in their beliefs on how science is to be funded in comparison to other social needs. ■