# Science Matters: Achieving Scientific Literacy

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SCIENCE MATTERS ACHIEVING SCIENTIFIC LITERACY

ROBERT M. HAZEN & JAMES TREFIL

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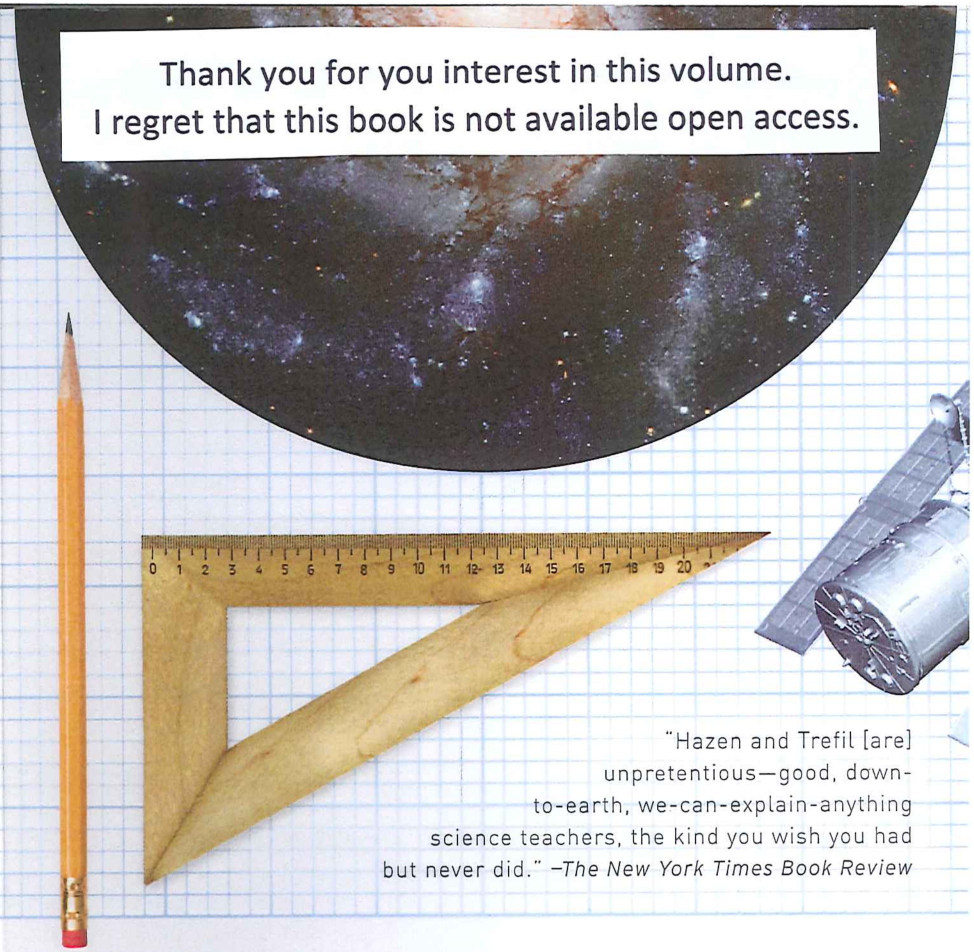

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# *Science Matters*

ACHIEVING
SCIENTIFIC
LITERACY

Robert M. Hazen
and
James Trefil

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*To Margee and Wanda*

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INTRODUCTION

# *Scientific Literacy: What It Is, Why It's Important, and Why We Don't Have It*

SOME TIME IN THE NEXT few days you are going to pick up your newspaper and see a headline like "Major Advance in Stem Cells Reported" or "New Theory of Global Warming Proposed." The stories following these headlines will be important. They will deal with issues that directly affect your life—issues about which you, as a citizen, will have to form an opinion if you are to take part in our country's political discourse. More than ever before, scientific and technological issues dominate, from global climate change, to the teaching of evolution, to the perceived gradual decline of American competitiveness. Being able to understand these debates is becoming as important to you as being able to read. You must be scientifically literate.

In spite of decades of well-meaning efforts, scientists and educators have failed to provide many Americans with the fundamental background knowledge we all need to cope with the complex scientific and technological world of today and tomorrow. The aim of this book is to allow you to acquire that background—to fill in whatever blanks may have been left by your formal education. Our aim, in short, is to give you the information you need to become scientifically literate.

## What Is Scientific Literacy?

For us, scientific literacy constitutes the knowledge you need to understand public issues. It is a mix of facts, vocabulary, concepts, history, and philosophy. It is not the specialized stuff of the experts, but the more general, less precise knowledge used in political discourse. If you can understand the news of the day as it relates to science, if you can take articles with headlines about stem cell research and the greenhouse effect and put them in a meaningful context—in short, if you can treat news about science in the same way that you treat everything else that comes over your horizon, then as far as we are concerned you are scientifically literate.

This definition of scientific literacy is going to seem rather minimal, perhaps even totally inadequate, to some scholars. We feel very strongly that those who insist that everyone must understand science at a deep level are confusing two important but separate aspects of scientific knowledge. The fact of the matter is that *doing* science is clearly distinct from *using* science; scientific literacy concerns only the latter.

There is no need for the average citizen to be able to do what scientists do. You don't have to know how to design a microchip or sequence a section of DNA to understand the daily news, any more than you have to be able to design an airplane in order to understand how it can fly.

But the fact that you don't have to know how to design an airplane doesn't change the fact that you live in a world where airplanes exist, and your world is different because of them. In the



same way, advances in fields like nanotechnology and bioengineering will affect your life in many ways, and you need to have enough background knowledge to understand how these changes are likely to occur and what their consequences are likely to be for you and your children. You must be able to put new advances into a context that will allow you to take part in the national debate about them.

Like cultural literacy, scientific literacy does not refer to detailed, specialized knowledge—the sort of things an expert would know. When you come across a term like "superconductor" in a newspaper article, it is enough to know that it refers to a material that conducts electricity without loss, that the main impediment to the widespread use of superconductors is that they operate only at very low temperatures, and that finding ways to remove this impediment is a major research goal in materials science today. You can be scientifically literate without knowing how a superconductor works at the atomic level, what the various species of superconductor are, or how one could go about fabricating a superconducting material.

Intense study of a particular field of science does not necessarily make one scientifically literate. Indeed, it has been our experience that working scientists are often illiterate outside their own field of professional expertise. For example, when we asked a group of two dozen physicists and geologists to explain to us the difference between DNA and RNA, a basic piece of information in the life sciences, we found only three who could do so, and all three of those did research in areas where this knowledge was useful. And although we haven't done an equivalent test on biologists—by asking them, for example, to explain the difference between a superconductor and a semiconductor—there is no doubt in our minds that we would find the same sort of discouraging result if we did. The fact of the matter is that the education of professional scientists is often just as narrowly focused as the education of any other group of professionals, and scientists are just as likely to be ignorant of scientific matters as anyone else. You should keep this in mind the next time a Nobel laureate speaks ex cathedra on issues outside his or her own field of specialization.

Finally, one aspect of knowledge is sometimes lumped into scientific literacy but is actually quite different. You sometimes see discussions of scientific literacy couched in terms of statements like "The average new employee has no idea how to use a BlackBerry" or "The average American is dependent on technology but can't even program a DVR to record when no one's home." These statements are probably true, and they undoubtedly reflect an unhappy state of affairs in American society. We would prefer, however, to talk of them in terms of *technological* rather than scientific literacy.

## The Scope of the Problem

The effectiveness of American science education has changed little since the 1987 commencement of Harvard University, when a filmmaker carried a camera into the crowd of gowned graduates and, at random, posed a simple question: "Why is it hotter in summer than in winter?" The results, displayed graphically in the film *A Private Universe,* were that only two of the twenty-three students queried could answer the question correctly. Even allowing for the festive atmosphere of a graduation ceremony, this result reveals the failure of America's most prestigious universities to turn out students who are in command of rudimentary facts about the physical world. An informal survey taken at our own university—where one can argue that teaching undergraduates enjoys a higher status than at some other institutions—shows results that are scarcely more encouraging. Fully half of the seniors who filled out our scientific literacy survey could not correctly answer the question "What is the difference between an atom and a molecule?"



These results are not minor blemishes on a sea of otherwise faultless academic performances. Every university in the country has the same dirty little secret: we are all turning out scientific illiterates, students incapable of understanding many of the important newspaper items published on the very day of their graduation.

The problem, of course, is not limited to universities. We hear over and over again about how poorly American high school and middle school students fare when compared to students in other developed countries on standardized tests. Scholars who make it their business to study such things estimate that fewer than 7 percent of American adults can be classed as scientifically literate. Even among college graduates (22 percent) and those with graduate degrees (26 percent), the number of Americans who are scientifically literate by the standards of these studies (which tend to be somewhat less demanding than our own) is not very high.

The numbers, then, tell the same story as the anecdotes. Americans as a whole simply have not been exposed to science sufficiently or in a way that communicates, the knowledge they need to have to cope with the life they will have to lead in the twenty-first century.

## Why Scientific Literacy Is Important

Why be scientifically literate? A number of different arguments can be made to convince you it's important. We call them,

the argument from civics
the argument from aesthetics
the argument from intellectual connectedness

The first of these, the argument from civics, is essentially the one we have been using thus far. Every citizen will be faced with public issues whose discussion requires some scientific background, and therefore every citizen should have some level of scientific literacy. The threats to our system from a scientifically illiterate electorate are many, ranging from the danger of political demagoguery to the decay of the entire democratic process as vital decisions that affect everyone have to be made by an educated (but probably unelected) elite.

The argument from aesthetics is somewhat more amorphous, and is closely allied to arguments that are usually made to support liberal education in general. It goes like this: We live in a world that operates according to a few general laws of nature. Everything you do from the moment you get up to the moment you go to bed happens because of the working of one of these laws. This exceedingly beautiful and elegant view of the world is the crowning achievement of centuries of work by scientists. There is intellectual and aesthetic satisfaction to be gained from seeing the unity between a pot of water on a stove and the slow march of the continents, between the colors of the rainbow and the behavior of the fundamental constituents of matter. The scientifically illiterate person has been cut off from an enriching part of life, just as surely as a person who cannot read.

Finally, we come to the argument of intellectual coherence. It has become a commonplace to note that scientific findings often play a crucial role in setting the intellectual climate of an era.



Copernicus's discovery of the heliocentric universe played an important role in sweeping away the old thinking of the Middle Ages and ushering in the Age of Enlightenment. Darwin's discovery of the principle of natural selection made the world seem less planned, less directed than it had been before; and in the twentieth century the work of Freud and the development of quantum mechanics made it seem (at least superficially) less rational. In all of these cases, the general intellectual tenor of the times—what Germans call the zeitgeist—was influenced by developments in science. How, the argument goes, can anyone hope to appreciate the deep underlying threads of intellectual life in his or her own time without understanding the science that goes with it?

## What to Do

The beginning of a solution to America's problem with scientific literacy, both for those still in school and those whose formal education has been completed, lies in a simple statement:

***If you expect someone to know something, you have to tell him or her what it is.***

This principle is so obvious that it scarcely needs defending (although you'd be amazed at how often it is ignored within the halls of academe). It's obvious that if we want people to be able to understand issues involving genetic engineering, then we have to tell them what genetic engineering is, how DNA and RNA work, and how all living systems use the same genetic code. If we expect people to come to an intelligent decision on whether tens of billions of tax dollars should be spent on alternatives to fossil fuels—development of biofuels, new nuclear power plants, wind turbines, and the like—then we have to tell them about the nature of energy in general and the potential benefits and risks associated with each specific energy source.

But this argument, as simple as it seems, runs counter to powerful institutional forces in the scientific community, particularly the academic community. To function as a citizen, you need to know a little bit about a lot of different sciences—a little biology, a little geology, a little physics, and so on. But universities (and, by extension, primary and secondary schools) are set up to teach one science at a time. Thus, a fundamental mismatch exists between the kinds of knowledge educational institutions are equipped to impart and the kind of knowledge the citizen needs.

So scientists must define what parts of our craft are essential for the scientifically literate citizen and then put that knowledge together in a coherent package. For those still in school, this package can be delivered in new courses of study. For the great majority of Americans—those whom the educational system has already failed—this information has to be made available in other forms.

And that's where this book comes in.

## About the Book

This book is dedicated to illustrating a statement that is one of academe's best-kept secrets: *The basic ideas underlying all science are simple.* In what follows, we present only the constellations of basic facts and concepts that you need to understand the scientific issues of the day.

Science is organized around certain central concepts, certain pillars that support the entire structure. There are a limited number of such concepts (or "laws"), but they account for everything we see in the world around us. Since there are an infinite number of phenomena and only a few laws, the logical structure of science is analogous to a spider's web. Start anywhere on the web and work inward, and eventually you come to the same core. Understanding this core of knowledge, then, is what science is all about.



The organization of this book reflects the weblike organization of science. It is built around nineteen general principles—call them laws of nature, great ideas, or core concepts if you like. Some of them transcend the compartmentalized labels we like to put on things, for, like nature itself, these great ideas form a seamless web that binds all scientific knowledge together. We devote the first five chapters of the book to these concepts, which will reappear in the remainder. They are absolutely essential to understanding science. You can no more study genetics while ignoring the laws of chemistry than you can study language by learning nouns and ignoring verbs.

Once the basic concepts that anchor all science have been established, we move on to look at specific areas, which we have organized in the traditional triad of physical, earth, and life sciences. We organize each of these categories around another set of great ideas that are appropriate to that particular field. For example, in the earth sciences one of the great ideas has to do with the changes of the planet's surface features in response to heat generated in its deep interior. This particular concept ties together a great deal of what we know about the earth, but at the same time depends on the deeper overarching principles contained in the first five chapters. By the time you've gone through all nineteen great ideas, then, you will have not only a general notion of how the world works, but also the specific knowledge you need to understand how individual pieces of it (the earth's surface, for example, or a strand of DNA) operate.

The great ideas approach to science has another enormous advantage. While you are learning about issues that are in the news today, such as drug-resistant microbes or human cloning, you will be building an intellectual framework that will allow you to understand the issues of the future. To see the importance of this approach, consider that when we first began discussing this second edition of *Science Matters* in 2006, the reality of global warming (and the consequent need for governmental action) was still hotly debated in political circles. A year later, thanks in part to record temperatures and an unprecedented shrinking of the Arctic ice cap, the reality of global warming is widely accepted and the debate has shifted to determining how much of the warming is caused by human activities and what actions need to be taken to deal with it.

It is entirely possible that problems that loom large today—the spread of bird flu, the ethics of stem cell research, the proliferation of nuclear weapons, and much more—may seem insignificant by 2020. But while we cannot predict *which* science-laden issues will dominate the headlines of the future, we know that some surely will. And since every future scientific advance will grow out of the ideas contained in this book, mastering them allows you to deal with not only today's problems, but tomorrow's as well.

There is a temptation, when presenting a subject as complex as the natural sciences, to present topics in a rigid, mathematical outline. We have tried to resist this temptation for a number of reasons. In the first place, it does not accurately reflect the way science is actually performed. Real science, like any human activity, tends to be a little messy around the edges. More important, the things you need to know to be scientifically literate tend to be



a somewhat mixed bag. You need to know some facts, to be familiar with some general concepts, to know a little about how science works and how it comes to conclusions, and to know a little about scientists as people. All of these things may affect how you interpret the news of the day. So if you find that the book is something of a potpourri, don't be surprised. That's the way science—like everything else in life—is.

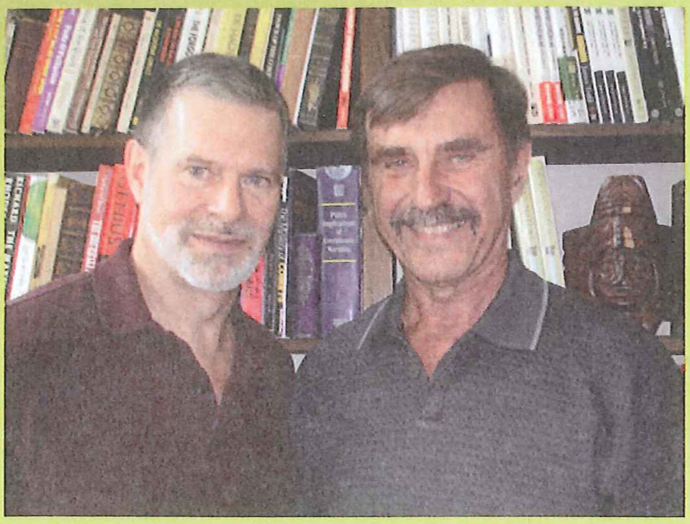
Finally, we hope that we can communicate to you another little-known fact about science: that it is just plain fun—not just "good for you," like some foul-tasting medicine. It grew out of observations of everyday experience by thousands of our ancestors, most of whom actually enjoyed what they were doing. Amid the collection of fact, history, logic, and policy questions that follows, we hope you occasionally catch a glimpse of two people who enjoy what they do—who occasionally thrill at the thought of the intellectual beauty of the universe we are privileged to live in and know.

## Note on the Second Edition

When we began the first edition of *Science Matters* in 1989 we proposed eighteen great ideas of science that we felt framed virtually all discoveries of the natural world and all advances in technology. We could not have foreseen many of the remarkable developments of the past two decades—nanotechnology, archaea, LEDs, cloning, dark energy, ancient microbial fossils and deep microbial life, evidence for oceans of water on Mars and lakes of methane on Titan, ribozymes, carbon nanotubes, extrasolar planets, and so much more. But all of these unanticipated findings fit into the existing framework of science. The core concepts of science have not changed, and we are unable to point to any fundamentally new scientific principle that has emerged during the

1990s or 2000s. Accordingly, while every chapter has been significantly updated, we have added only a single new chapter on the explosion of advances in biotechnology. We conclude that the experience of the past two decades underscores the value of the great ideas approach to achieving scientific literacy.

# *Science Matters*



**James Trefil** (right) has authored or coauthored numerous books on science for the general audience. His interest in science literacy began with a contributed essay to E. D. Hirsch's Cultural Literacy and continued with his work on the Content Review Board for the National Science Education Standards. He is a frequent lecturer on science and the law at state and federal judicial conferences. He received undergraduate degrees from the University of Illinois and Oxford University. After receiving a doctorate in theoretical physics from Stanford University, he held post-doctorate and faculty appointments in Europe and the United States. He is the Clarence Robinson Professor of Physics at George Mason University. He has made contributions to researching elementary particle physics, fluid mechanics, medical physics (including cancer research), and the earth sciences. Trefil was awarded the Gemant Prize of the American Institute of Physics for his efforts to present science to the public. His most recent book is *Science in World History*.

**Robert M. Hazen** (left) is the Clarence Robinson Professor of Earth Science at George Mason University and Staff Scientist at the Carnegie Institution of Washington's Geophysical Laboratory. Hazen developed a fascination for rocks and minerals as a child growing up in mineral-rich Northern New Jersey, and he pursued that interest as an undergraduate at the Massachusetts Institute of Technology. After receiving a doctorate in earth sciences from Harvard University, he spent a year at Cambridge University as a NATO Postdoctoral Fellow. In addition to teaching courses on scientific literacy, scientific ethics, symmetry in art and science, and visual thinking, he performs research on the roles that minerals may have played in the origin of life. His current studies explore the hypothesis that life arose in a deep, high-pressure environment. Hazen is active in presenting science to the public. He developed a 60-lecture video version of the textbook *The Joy of Science*, which is available nationally through The Teaching Company. He has appeared on numerous radio and television shows, including NOVA and Today. His most recent popular book is *The Story of Earth*.