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CHAPTER
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Scientific Literacy: The Enemy Is Us

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Pick up a newspaper any day of the week and you will find a dozen articles that relate to science and technology. There are always stories on the weather, energy, the environment, and medical advances—the list goes on and on. Is the average American prepared to understand the scientific component of these issues? I am afraid the answer, in almost every case, is no.

In this chapter, which is adapted in part from a previous report (Hazen and Trefil, 1991c), I will first describe my perceptions of the nature and origins of the national scientific literacy problem and then propose a solution that U.S. science educators can implement with reasonable ease and with a sense of optimism.

I want to share a few horror stories about the deficiencies in U.S. science education. Many others have presented similar examples (see, for example, American Association for the Advancement of Science [1989], Bishop [1989], and National Research Council [1990]). The series of personal anecdotes I describe may, at first, seem very different and perhaps unrelated. Yet, I think these separate incidents can be tied together to create a much larger and more sinister picture of the way science is taught in the United States.

The first is the story of my daughter Elizabeth. She is a seventh grader and about as bright as any student you would ever want to meet. Year after year she has been required to memorize lists of vocabulary words in science. Her sixth-grade science teacher introduced her to terms like *batholith*, *saprophyte*, *nekton*, and *hyphae*. She had to define Hertzsprung-Russell diagrams and Fahnestock clips, all in the sixth grade. Ten- and 11-year-old children are being taught vocabulary that the average doctoral-level scientist does not know.

Elizabeth also had to memorize the names and accomplishments of 40 African-American scientists. That is a laudable thing to teach, but rather than learn about these individuals as real people who had aspirations, who had tremendous roadblocks to their careers, and who ultimately triumphed, she had to memorize a list of 40 names on one side of a piece of paper and 40 accomplishments on the other: the students had to match the pairs. For example, she had to remember that Caldwell McCoy worked to create energy from magnetic fusion. Unfortunately, the children in the sixth grade were never told about nuclear fusion, nor had they the slightest notion of what magnets had to do with fusion energy.

My daughter is very good at memorizing things, and she did quite well in the class. And now she hates science.

My son Benjamin is in high school, and he is also a fine student. Like most high-school students, he takes science, with weekly laboratories where everyone mixes the exact same amount of the exact same chemicals and gets, one hopes, the exact same results. The standard titration experiment (the one where solutions turn pink) was one of his required exercises. If Ben wanted a good grade, he had to get the right answer; there was no margin for error, no chance to think about other experiments, and no opportunity to see what would happen if he mixed things in slightly different ratios.

Ben is pretty clever and he figured out how to do the experiments. When I asked Ben what an acid or a base is, he looked at me with a blank stare—he did not have the vaguest idea. Now, Ben hates science, too, and he asked me recently, "Why would anyone want to do this sort of thing for a living?" That is a tough question for a scientist to be asked by his child.

I now move to the college level. The scene is Harvard University on the festive 1987 graduation day as recorded in the film *A Private Universe* (Pyramid Film Video, Santa Monica, Calif.). A group of seniors, about 25 in all, was asked, "Why is it warmer in the summer than it is in the winter?" Granted, it was graduation day, everybody was in their festive robes, champagne corks were popping, and so forth. Of those 25 graduating Harvard seniors, however, only 2 answered correctly. The vast majority said it is warmer in the summer because the earth is closer to the sun, an explanation that should make any elementary-school science teacher cringe.

A similar survey at my own university, George Mason, revealed that more than half of the graduating seniors could not describe the difference between an atom and a molecule. There is no doubt that we are producing a generation of college graduates who do not know the most basic facts about science.

What about working scientists, those of us who are in the elite? I did an informal survey among two dozen of my colleagues in the earth sciences. Each was asked a very basic question in biology: "In simple qualitative terms, what is the difference in function between DNA and RNA?" (They are two fundamental molecules present in all life. The first carries the genetic code; the second interprets it.) Of two dozen geologists, only two could answer the question, and both of them were biogeochemists engaged in a study of fossilized DNA remnants in rocks.

To even out the record, I asked a group of biology professors, "What is the difference between a semiconductor and a superconductor?" Apart from a bad joke about the local symphony orchestra, not one biologist could respond to that question.

One might think that my informal survey included only second-rank scientists, that the cream of the crop really possesses a broad general scientific knowledge. Unfortunately, it is not true. I recently engaged a Nobel Prize-winning chemist in a conversation about the 1989 San Francisco earthquake. In the course of that discussion I mentioned plate tectonics. He looked at me and said, "What's plate tectonics?" When I told him of the transformation that has taken place in the earth sciences in the last few decades, he seemed only politely interested. He certainly was not the slightest bit concerned that one of the most important discoveries in our understanding of the planet had completely passed him by.

Each of these stories about science is disturbing in its own right. But taken together, they present a truly bleak picture of the state of American science education. At every level we are failing to provide students with the information they need as citizens. Elementary school children are learning that science is difficult, boring, and irrelevant to their day-to-day lives. College students are graduating without knowing the most basic concepts about their physical world. And even working scientists are often scientifically illiterate outside their own narrow specialty.

What is going on? Why has the system failed so many people? My colleague Jim Trefil and I believe the answer boils down to the misdirected priorities of scientists ourselves. If you listen carefully to most scientists when they talk about the scientific literacy crisis, what they really mean is that fewer and fewer people are becoming scientists. At present, about 1 percent of the U.S. population are scientists, and as far as most scientists are concerned, the other 99 percent are of little concern.

In a sense, it seems that most scientists' educational objectives are to try to make everyone a scientist. We start out with that as a goal, and then we weed out the unworthy. We subject children at earlier and earlier ages to more and more big words, mathematical rigor, and experimental abstractions. Then, as children get turned off, a significant number of educators advocate teaching even more big words at an even earlier age to reverse the trend. They press for more mathematics and additional fancy experiments. Is this strategy going to attract more children to science? I think not.

I attended a junior high school physics class recently where this problem was highlighted. The teacher faced the classroom and said, "Today we are going to talk about gravity." Then he turned to the blackboard and, as he wrote, said, "This is the equation for gravity," and proceeded to analyze the variables.

What a terrible thing to do to a group of 12-year-old children. Gravity is jumping off a chair, dropping a ball, or Michael Jordan doing a 360-degree slam dunk. Look at your day-to-day lives and see how often gravity comes into play. Children need the chance to recognize that there are only a few physical forces that control our lives. Then, if they are interested enough—if they want to know how they might get a satellite into orbit—you can write down equations and apply them. Until children understand, however, that gravity is a force that affects them every day of their lives, the equation means nothing. It is a needless abstraction.

How many students in that class will decide to devote their lives to science? The chances are, none. Our biggest mistake as educators is that from the earliest grade we try to make all of our students miniature scientists. If they succeed at one stage, then they go on to bigger and harder science. Eventually, at some level, almost all drop out—almost all have failed. Scientists have become like an elite priesthood of knowledge: Only the worthy who have completed the rites are allowed in. No wonder so few Americans want to become scientists, and no wonder there is so much mistrust of science and scientists. What other academic field makes the majority of students feel like failures?

The situation is, if anything, worse in U.S. colleges and universities than it is in the elementary schools. Two problems pervade the organization and the presentation of science at the college level (Hazen and Trefil, 1991a,b). First, almost all science courses, even those for first-year nonscience students, are geared for science majors. Such courses are intended to give a foundation for further study. As a result, they rarely provide any sort of overview of science and do little to foster scientific literacy among scientists or nonscientists. Second, science courses rarely integrate physics, chemistry, biology, and geology. Students must take courses in at least four different science departments to gain even a basic level of literacy in all the sciences.

A number of very successful departmental courses have addressed the first problem. Offerings like Physics for Poets—courses designed specifically for nonscientists—do a very good job of introducing a specific discipline. But these courses still leave the nonscience major with exposure to only one branch of science. There is little chance that a student in Physics for Poets will learn about modern concepts of genetics or plate tectonics. In short, the science curricula of most colleges and universities fail to provide the basic science education necessary to understand the science and technology issues facing this society.

The ever-increasing specialization of science has as one of its sorriest consequences the fact that most working scientists are themselves scientifically illiterate. I am a perfect example. The last time I took a course in biology was in ninth grade, long before the modern developments in genetics appeared in any textbook. In college I studied lots of earth science, and in graduate school I studied lots more. But no one ever suggested that I take a biology course, and I was not likely to waste my time reading about something that my professors did not expect me to learn.

From that distant day in 1962 when I last dissected a frog until just a couple of years ago when I began teaching general science, I was about as ignorant of modern biology as it was possible to be. We are a society that has lost the ability to teach general science at any level, because there is almost nobody who knows enough to teach it.

The United States is number one at producing specialized professional scientists, scientists that have the research skills, the insights, and the abilities to do top-notch research to lead our country in technology and to lead the world in teaching new doctorates (even if most of those students come from other countries). Our specialization has come at a price. National science leaders, the people who are best at playing the research game, have fostered an education policy so concerned with producing the next generation of specialized scientists that the education of the 99 percent who are not going to be scientists has gone by the wayside. And this policy has backfired, because it is turning off U.S. science students in record numbers.

The problem is daunting, but there is a realistic and straightforward solution. Our specific solution addresses the scientific literacy crisis at the college level, but the same principles could be extended to both pre- and postcollege learning.

Jim Trefil and I have developed a course for undergraduate nonscience majors at George Mason University. The university's science core curriculum committee has recommended that all nonscience majors take this course in their first year; that course should be followed by a two-semester laboratory course in physics, chemistry, geology, or biology. In this way, every student receives an introductory overview that is followed by a specific science course that gives them some experimental rigor, that introduces laboratory technique, and that examines the analytical process in doing specific scientific experiments. This pairing starts with an integrated view of physics, chemistry, biology, and earth science and then explores one subject in greater depth.

It must be emphasized that scientific literacy does not mean producing more scientists. That cannot be the goal of effective general science education. The principal objective is to give all Americans the information they need to understand the kinds of technological and social issues that confront us every day. This knowledge is not the specialized stuff of the experts; it is an eclectic mixture of vocabulary, general principles, some history, and some philosophy. This core knowledge changes only gradually with time, in contrast to the constantly shifting events in the news. If students can take a newspaper article about genetic engineering, the ozone hole, or chemical waste and put those in a meaningful context—if they can treat science in the same way that they treat any of the other pieces of information, like sports, business, or economics, that comes their way—then they are scientifically literate.

The major challenge we face as science educators is that most societal issues concerning science and technology require a very broad range of knowledge. To give just one example, consider nuclear waste. To understand nuclear waste, you need to know how nuclei decay to produce radiation (physics), how radioactive atoms interact with the environment (chemistry), how radioactive waste can enter a geologic system (earth science), and how radiation affects living things (biology). Students cannot begin to understand the nuclear waste problem if they have studied only physics, chemistry, or biology. Similarly, many other issues, including global warming, space research, alternative energy resources, and medical technologies, depend on a whole spectrum of scientific concepts. Scientifically literate scientists and nonscientists alike need to understand a little bit of several disciplines to cope with these issues.

Science forms a web of interconnected knowledge. The key to producing scientifically literate graduates is to recognize that there are a few basic overarching ideas in science, ideas that connect all of our physical experience. We live in a universe of matter and energy—that is all there is with which to play the game of life—and science is simply the set of rules about how matter and energy behave. Once students are introduced to these basic principles about matter and energy, they begin to see science as a special way of understanding their universe. They learn to place science in a much broader human perspective.

We organize our course, Great Ideas in Science, around a series of about 20 overarching principles. The list of great ideas is neither obvious nor immutable (Culotta, 1991). Any scientist could come up with a compilation of 20 or so key concepts. Compare a dozen different lists and 8 or 10 ideas will appear just about every time. Newton's laws of motion, the laws of thermodynamics, and the concept of the atom are common to all scientific disciplines, for example.

The most basic principle, the starting point for all of science, is the idea that the universe can be studied by observation and experimentation. It is remarkable how many students—even science majors—have no clear idea how this central concept sets science

apart from religion, philosophy, and the arts as a way of understanding our place in the cosmos.

Once students understand what science is, then they can appreciate the basic principles shared by all sciences, things that are traditionally covered in early physics courses: Newton's laws that govern force and motion, the laws of thermodynamics that govern energy and entropy, the equivalence of electricity and magnetism, and the atomic structure of all matter. These are not abstract concepts. They apply to everyday life, explaining, for example, the compelling reasons for wearing seat belts, the physics of a pot of soup, and the contrast between static cling and a refrigerator magnet. In one form or another, all of these ideas appear in virtually every elementary science textbook, but often in abstract form. We should strive to make them part of every student's day-to-day experience.

Once the general principles have been laid down, we can look at specific natural systems such as galaxies, the stars, the earth, or living things. For each of those systems, additional principles must be stated. In astronomy, for example, students learn that stars and planets form and move according to Newton's laws, that stars eventually burn up according to the laws of thermodynamics, that nuclear reactions fuel stars by the conversion of mass into energy, and that stars produce light as a consequence of electromagnetism.

Two basic ideas—plate tectonics and earth cycles (rock, water, and atmosphere)—unify the earth sciences. The laws of thermodynamics decree that no feature on the earth's surface is permanent. This principle can be used to explain geologic time, gradualism, and the causes of earthquakes and volcanoes. The fact that matter is composed of atoms tells us that individual atoms in the earth system—for example, in a grain of sand, a gold ring, or a student's last breath—have been recycling for billions of years.

Living things are arguably the most complex systems that scientists attempt to understand. We identify five basic principles that apply to all living systems: all life is based on chemistry, all life is made up of cells, all life uses the same genetic code, all life evolved by natural selection, and all forms of life are interconnected as parts of ecosystems.

The great ideas approach has a tremendous advantage for students and for teachers. Any issue of scientific or technological importance can be introduced as a way of illustrating the general principles. We frequently use examples from recent newspapers: New materials emphasize how atoms combine to cause distinctive properties; environmental concerns illustrate ideas of ecology; space probes raise questions about the planets. It is likely that the issues that loom large today—AIDS, drug abuse, and the hole in the ozone layer—may seem insignificant in a few years, while new issues will undoubtedly come to take their place. By focusing on general principles, whatever issue comes along, the teacher can immediately integrate that into the basic framework of the course. Furthermore, each teacher can choose examples to suit his or her interests and style, and the underlying principles will remain the same.

Another important benefit of the great ideas format—one that has special relevance to agricultural education—is that many important technological fields are poorly represented by traditional science departments. Computer and information technology, brain research, and medical science often are not integrated into traditional courses in chemistry and physics. Agriculture and natural resources represent other fields in which the traditional physics, chemistry, or biology courses do not touch on important issues. By teaching a general principles course in science, every illustrative example can be chosen from a favorite discipline, without sacrificing generality.

We also are able to look at science from a rich variety of viewpoints using these general principles. For example, Newton's laws of motion are among the central ideas in science, but students should also learn things like when Isaac Newton lived, how he incorporated the earlier work of Galileo and Kepler into his system, and how Newton's work influenced the philosophy of the Enlightenment. Newton's laws can be used to illustrate such practical examples as why people should wear seat belts, the launch of a space shuttle, or even the difference between football linemen and quarterbacks. Newton also provides an excellent starting point to discuss the relationship between science and technology, the importance of experimentation in science, and the scientific method—all key concepts that are not covered in most science courses.

The most frequent objection to the Great Ideas in Science course is "No one will be able to teach it." Such a criticism of our course is, in itself, a serious indictment of the science education system. If professional science educators are unable or unwilling to learn the most basic principles of other scientific fields, then how can we expect nonscientists to gain any level of scientific literacy themselves? If a physics teacher refuses to learn biochemistry or biologists shun plate tectonics, why should students care at all about these subjects?

Ideally, one faculty member should teach the entire course. We have found that many faculty members at George Mason University are eager to do this. During the 1990 spring semester, eight faculty members representing all the science departments attended the course and are now ready to teach it themselves. None of us is an expert in all the fields covered, and student's questions often leave us stumped. But it provides a valuable lesson to the class when you say, "I don't know the answer to that question, but I will find out." What better way to emphasize to students that science is an ongoing process of learning?

An obvious alternative is to have several faculty members teach in their own disciplines; thus, chemists, geologists, and biologists could stay close to their own turf. We discourage such an approach

for several reasons. One key theme of the course—that the sciences are integrated and they form a seamless web—is lost. Specialists tend to slip into confusing jargon and dwell on unnecessary detail, thus defeating the purpose of the overview. Finally, students may well ask why they must master a range of scientific topics when the faculty members appear to be unwilling to do so.

Student response to this course has been overwhelmingly positive. Students complete detailed course evaluations at the end of each semester, and they have always placed the course in the top 10 percent of course offerings at George Mason University. Many students who are nonscience majors have remarked that the course is the first one to make science seem relevant to their everyday lives. Surprisingly, many science majors said it was the first time they understood what they were doing as scientists; as specialized science majors, they had never seen the big picture.

Science educators throughout the country have created a system that alienates science students from their earliest years. At every grade level the accumulated vocabulary and the mathematical abstraction winnows out students. By returning to general science courses for all students, colleges can, in some measure, reverse the trend. Our goal must be to produce college graduates who can see that scientific understanding is one of the crowning achievements of the human mind, that the physical universe is a place of magnificent order, and that science provides the most powerful means for discovering knowledge that can help us to understand and shape our world.

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