ROBERT POLLACK

SCIENCE AS A CREATIVE PROCESS

DISCOURSE

What a scientist does should be taught as science to everyone, not only to other scientists.

Neither an education in general nor knowledge of science in particular are listed in the Bill of Rights. To participate fully in our national life, however, we must have the abilities to read, write, and understand the events of the day. Since literacy per se is not yet fully achieved in our country, it may seem fatuous to claim that it is insufficient. But without scientific literacy as well—a facility with numbers, combined with an acquaintance with the creative process called "science"—Americans find themselves increasingly unable to exercise their Constitutional rights in their daily lives.

America's colleges and universities are frequently taken to task for failing to fill this gap in our students' education. F. H. Westheimer has argued, for example, that the solution lies in creating more requirements for science courses in our institutions of higher education.[1] I agree. Westheimer also argues, however, that the content of such courses should be no more than a collection of the products of the various scientific disciplines. Here I disagree.

Some facts must be learned, to be sure. But for the nonscientist, such facts are best taught as part of demonstrating to students how scientists think and work. Our own creative monuments—the great papers of any science—are the proper texts from which to teach science to the nonscientist.

Science is what a scientist does

What a scientist does should be taught as science to everyone, not only to other scientists. A scientist asks questions about nature, and then tells stories about the answers she or he gets back. The asking process is called "experimentation," and the storytelling takes place through publications, meetings, grant reviews, and the like. The stories have kept to the same format first used by Galileo: A question is rephrased as a model, an imaginary construct that can explain a piece of nature, but that may or may not be true. The scientist then proposes to test the model by direct experiment, which either verifies or falsifies the model, causing it to become the best current explanation of how something in nature works or the source of a new and improved testable model which then gets tested again, and so forth.

At the same time, the visible product of this process is an ever-increasing store of information about how nature works. Sometimes that accumulated information has an immediate utility in the real world; sometimes it does not. In any case, the confirmation of models is the central purpose of the experimentation, while the resultant data bases and sets of observations are a more-or-less useful by-product. Credit in science often goes to the elucidator of a model that explains more data, and not to the compiler of data who cannot or will not subsume the data in order to test a model. Indeed, one form of good taste in science is asking the largest possible *answerable* question at any moment. The creative element lies in knowing how far to go, because one step larger becomes untestable by definition and is therefore a waste of the scientist's time. The report of a successful test of a new model can be an exciting piece of literature, as well as a triumph of insight. Such reports can and should be made accessible to anyone learning about science.

There are two valid reasons for trying to give every American student a legacy of knowledge about the scientific process. First, as the universe becomes comprehensible through science it becomes available for our purposes. As citizens we have an obligation to be knowledgeable because the products of science will be used in our names. Second, the creation of a testable model is the scientist's response to innate curiosity, which has

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much in common with the creative responses of writers and artists. We should, therefore, teach science just as we teach music or literature.

Neither reason has much to do with what is called "science education" in America today. The process is not taught. The data bases that result from the process are taught as the science, while both consequences and origins are relegated to other parts of the curriculum or not taught at all.

Of course some people necessarily must learn science well. These are the scientists' student protégés. Science is a guild, and the apprenticeship is a period of teaching and learning that may run to ten years or more. Members of the guild do not teach science the right way, except to other scientists, nor are scientists recruited into the guild through teaching. Rather, they are self-selected, usually early in adolescence, which is why reading science fiction, hacking on computers, or indulging in the smelly pleasures of a home chemistry lab are the initial "courses" in the education of many—if not most—practicing scientists.

But the science education that occurs among scientists is hermetic, and it will not fill the gap in this country's general scientific literacy. Outside the guild, scientists often place teaching below a host of other priorities, and teaching nonscientists at the very bottom, as if it were completely disconnected from their interests. It is unfortunate that the social norms of many university-based science departments emphasize research at the expense of teaching nonscientists, while basic research has so many centers of excellence in institutions that contain liberal arts colleges. Certainly we need to find ways to make teaching science outside the guild a more necessary part—and one recognized as such—of one's career as a university scientist.

Marie Sklodowska Curie

Another impediment to teaching science properly to nonscientists is the temptation to teach only what science students want to learn. That is not irresponsible, but it is lazy. Teaching science as a list of results rather than as a process is a common response to strong market demand. To those who want to use the results in nonscientific ways, how the results came to be known tends to be of less interest than the results themselves.

A variant of this kind of problematic curricular planning is teaching only what nonscientists are thought to need to know. Emphasizing results over the process of experimentation avoids the issue of motive and protects the scientist from her or his responsibilities as a citizen. There is, after all, a moral dimension to all human activities, even the purest research.

Ernest Rutherford

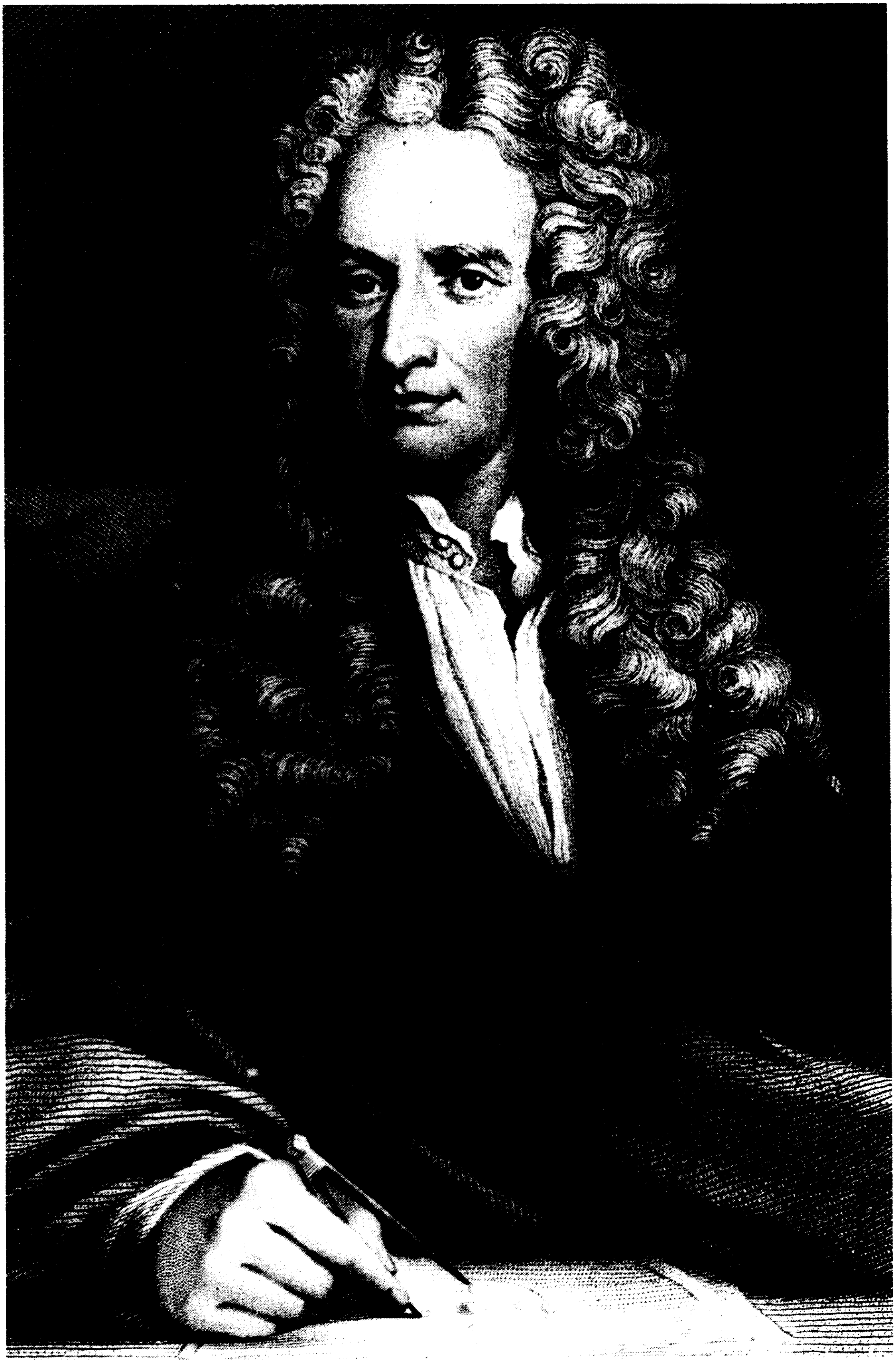
Finally, some of us teach about the products to retain our authority over the process. Like the Nile temple priests who used geometry and the calendar to predict floods and then map the fields, we enjoy the authority that the process of science bestows on us. Proper teaching ultimately dilutes such authority. Many of my colleagues do seem to take—unconsciously, of course—great pleasure in knowing something that is too difficult to explain to someone who has not wanted to put in the time required to become a scientist.

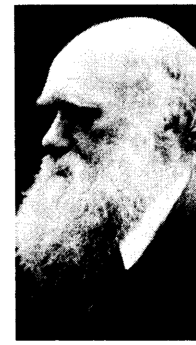
Process and product

We must somehow replace a good part of the current science curriculum with one that is rooted in the larger culture, one that explains how science is done. As noted by Westheimer, the science requirement at my own institution, Columbia College, is—in the words of our bulletin—"intended to provide the opportunity to learn what scientists do, how they think, what kinds of questions they consider, what procedures they develop to evaluate the results of their research, and in what forms they present their knowledge."[2] We require two semesters of science; the students may choose from among a set of courses whose contents cover, in part, these expectations.

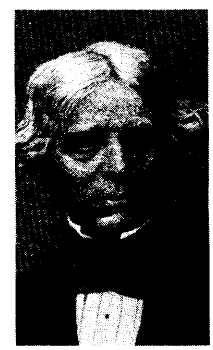
The one interdepartmental course designed specifically to fit this description has been offered with excellent results for seven years. "Theory and Practice of Science," by using original science papers, shows what scientists actually do. The question "What is science?" is posed at the start, and as students read the papers and study the theory and experiments behind those papers they begin to piece together an answer more satisfactory than what any scientists could tell them. Our nonscientists do struggle with the material, but in the end they have an understanding of science that is not imparted, but discovered. They see a few products, but not at the expense of the process, and they can distinguish science from other methods of inquiry.

In the first semester of the course, mathematics is taught from the ground up. Students learn about number systems, methods of pattern recognition, the difference between a theorem and a physical law, and the concept (and examples) of a mathematical model. Then the discovery of nuclear fission is taught by a physicist. The unit begins with excerpts from Faraday's *Experimental Researches in Electricity*, and continues with papers by the Curies, Thomson, Rutherford, Bohr, and





Albumen print of Charles Darwin by Julia Margaret Cameron, ca. 1880



Michael Faraday

Sir Isaac Newton

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others. The section concludes with two "fission" papers—one by Hahn and Strassman, the other by Meitner and Frisch—and a discussion of the second paper is accompanied by an on-site demonstration of the fission experiment.

The second semester begins with more mathematics, but in this semester the emphasis is on the basics of discrete probability, information theory, and statistics. Then a biologist teaches a set of papers starting with Mendel's "Experiments in Plant Hybridization." Students read Darwin, Morgan, Lederberg, and others, leading to Watson, Crick, and the genetic code.

Examinations are themselves science papers, and after the biology semester, the exam is usually drawn from a current issue of *Science*, *Cell*, *Nature*, or the *Proceedings of the National Academy of Sciences*. Students are able to summarize and analyze these papers, and they are usually able to propose clever and stimulating next steps in the process.

To teach science to a class of scientifically naive students in this way permits us to raise the most serious scientific questions of our day in order to examine the responses of individual scientists. Unanswered questions become the norm, not the exception, since the emphasis is on an open-ended process of model building rather than on the elaboration of a mass of "known" facts.

Scientists at Los Alamos National Laboratory, 1946: Norris Bradbury, John Mantley, Enrico Fermi, J. M. B. Kellogg, J. Robert Oppenheimer, Richard Feynman

Placing science in history

While history affects the role of science in society, it is important to emphasize that the history of science is not the same as the place of the scientific process and its results in history. A course built around dates and precedences for discoveries in science is bad history and as boring as the worst sort of science teaching.

On the other hand, intellectually rigorous modern history cannot exclude science. The ancient questions, "What is the universe made of?" and "What am I made of?" are so large that their answers have been progenitors of whole religions and the foundations of vast empires. Scientists are not accustomed to seeing testable predictions put to such questions because we expect our arguments to come wrapped in quantitation and specificity. Nevertheless, these questions are the very root of our profession, and they place us in our larger culture. Numbers are indeed the *lingua franca* of science, but the language is not the statement. The statement of science is the testable prediction. The creative event of science is the demonstration that the prediction was correct; from this demonstration will follow major consequences for the next prediction and perhaps for society as well.

Once we understand this, our teaching of science can become quite different from our teaching the results of science, or our teaching the history or even the language of science. I do not claim that it is necessary—only that it is possible—to take the next step. Teaching the process of science in its full context requires acknowledging fully the historical context, the political pressures, the personal lives, and the human interactions of the scientists whose work is being taught. To carry this a step further, teaching science in this way cannot properly be divorced from teaching politics or teaching art history. All must be embedded in a coherent curriculum, one in which argument and discussion are encouraged, in which all are seen as open-ended rather than complete.

Science in the next century

We have to find ways to keep the attention of talented scientists focused more of the time on teaching outside of their guilds. Those of us who are trying to make ourselves understood to the nonscientific world are sailing against a strong tide. That tide pushes us to present results, to measure creative insight indirectly by knowledge of results: in other words, to train rather than to teach. The tide is reinforced, in turn, by considerations of money. The reward systems of this country, even in universities, do not value this or any other sort of teaching as much as they ought. While such teaching is almost always appreciated as a service, it is rarely rewarded directly within the professional guilds, and it is always at risk of being just tolerated or even disdained.

If we do not change this, the message to young scientists on our faculties is very clear: Avoid introspection; avoid the process except to use it; learn the technology; and, at all costs, publish. I do not think that any university or college can do more than serve well its own students and faculty. But together the faculties and administrations of many universities could, if they chose to, consortially make some changes that would begin to encourage and reward the sort of true teaching I have described.

Second, numeracy must be the prerequisite or corequisite of any serious science course. The language of science, as it is used by practicing scientists, is based on numbers. Certain members of social sciences departments can reasonably be expected to teach the scientific process well, providing that they introduce the mathematics. The mathematics of science needs to be taught in as many departments as possible, but in the way a language is taught: through use rather than through memorization.

Finally, if the effective teaching and learning of science is going to be part of America's third century, local boards of education, private foundations, and state and federal governments must increase their support in this area. These are difficult times in which to try out new ways of teaching in our institutions of higher education. Proposals to cut support for curricular innovations or for education in general are rife, and when implemented they have predictable consequences. We must recognize that our country's security is threatened by such cuts. What greater gift to our adversaries than voluntarily and deeply damaging our chances of keeping pace with the process and products of science? These products will be mysteries to an increasingly larger fraction of the population until we overhaul the way we teach science to our nonscientific citizens. □

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1. F. H. Westheimer, "Are Our Universities Rotten at the 'Core'?" *Science* 236 (June 5, 1987).
2. *Columbia University Bulletin* (Columbia College, New York, 1987), 46.