

The relevance of physics

Why not show how physics draws upon and adds to other aspects of civilization, instead of teaching it as an isolated discipline or as a glorious entertainment for mathematical wizards?

Gerald Holton

MAGNUM PHOTOS



What reasons are there for thinking physics to be of basic importance? What is the present relevance of science? There are at least five parts to a complete answer. I want to sketch these here, in a frankly didactic manner, in a way that might make sense to an earnest, beginning student. (He will also see some worrisome aspects of the present state of science, but it is not my purpose to rehearse those here.) That questions about "relevance" have in the last few years become almost clichés does not change the need to be clear about the subject; we shall attack it head on.

Intellectual excitement

Even a student in a first physics course can and must, at some points during his study, feel the intellectual excitement that accompanies the understanding of human achievements, the kind of achievements that the history of physics can proudly boast of. This sort of excitement can come from the explanation of planetary motion just as it can come from the discovery of the internal structure in *King Lear*. The student may have felt it, keenly and suddenly, when a theory showed the connection between apparently separate parts of experience, when a laboratory experiment succeeded after many tries, when the computed planetary orbit closed, or when a long derivation that seemed to ramble on and on came suddenly to an end, as does a Bach fugue.

One glimpses, at such a moment, that the sort of knowledge physics leads to does crystallize the confused world of phenomena. Here is a way to see nature's clarity; here is a way to find the necessity that guides all things. Recall how lyrical Johannes Kepler became in the *Harmonice Mundi* when he found that T^2/R^3 , the ratio of period squared to major semiaxis cubed, is a constant

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for all planets. We must not dismiss such a moment of high emotion; it *belongs* in science and in the teaching of science as well. It is a real and profound experience, an intellectual excitement that every scientist has when he discovers something new or even when he first reads of a beautiful piece of work done by someone else. If we did not treasure such experiences, life would grow dull indeed. The joy of intellectual engagement in the deepest phenomena of the material world and the joy of discovering therein the success of one's own rational and intuitive faculties are among the most relevant and ennobling experiences one can have.

Scientists have often praised the simplicity of physics, in which only a few really deep laws suffice to deal with the myriad of apparently different observations. From the very beginning of a physics course, when we quickly abandon the gyrations of a falling leaf as a useful beginning for the study of motion, we learn to look for simple commonalities in all behavior. We have been seeking principles that will unify diverse cases, whether it be a falling leaf in one's garden or the turning of an unseen solar system at the edge of the universe. Nothing is more astonishing than that such a universal physics is possible; it is exhilarating to find that the most distant hydrogen atom is built on exactly the same principle as is the nearest one. All the laws of physics that govern the structure of matter and its behavior in space and time have that universality.

Albert Einstein once expressed these thoughts in a memorable way. Physical theory, he said, has two ardent desires: to gather up, as far as possible, all pertinent phenomena and their connections, and to help us

possible the utopian and seemingly arrogant aim of knowing *why nature is thus and not otherwise* . . . Thereby one experiences, so to speak, that God Himself could not have arranged those connections in any other way than that which factually exists, anymore than it would be in His power to make the number 4 into a prime number. This is the Promethean element of the scientific experience . . . Here has always been for me the particular magic of scientific effort."¹

Three and a half centuries earlier, Kepler had used almost the same words. In the preface of his first book, the *Mysterium Cosmographicum*, he announced that he wanted to find out, with respect to the number, positions and motions of the planets, "why they are as they are, and not otherwise." To a friend he wrote about the same time that, with regard to numbers and quantity, "our knowledge is of the same kind as God's at least in so far as we can understand something of it in this mortal life."²

These were by no means sacrilegious thoughts; Kepler was a pious man. As he often stated—and many scientists since then have agreed with him—the world that God made stands before our minds as a kind of puzzle for us to solve so that we may prove we are worthy of the mind given us for that purpose.

It would then be quite wrong to present physics either as an isolated, bloodless body of facts and theories with mere vocational usefulness, or as a glorious entertainment for an élite of mathematical wizards. (Some of the best physicists have, as a matter of fact, been themselves not particularly good at mathematics.) Physics is the study of what makes the whole world go, and it is too beautiful to be kept secret from any student, no matter what his career plans may be. To live with more joy and intelligence one must know the

world in which one lives, and this surely includes the majestic yet simple order physicists have found in our universe. Without such a study, as Galileo said, one may be lost in a labyrinth and not even know it. To be ignorant of physics may leave one unprepared for living in one's own time—as an intelligent spectator no less than as an effective wage earner, citizen or policy maker.

Benefits of "spin-off"

A very different way of seeing the relevance of science is in terms of the effect science sometimes has in helping to prepare the base for technological advance. We speak here not of the long-range, slower effects but of the quick "spin-off," the intentional use of basic science "for the relief of man's estate," in the phrase of the 17th-century philosopher Francis Bacon.

Many students and critics of science appear to have only this immediate aspect in mind when they use the word "relevance." Useful though science may be in this sense, it would be quite wrong to settle merely for the assistance physics can give, say, to the study of such problems as building a dam or overcoming pollution. We say this for two reasons: First, there need be relatively little connection between today's basic physics research and current technological advances or requirements. The gadgets and devices now being produced by industry, even if they are as sophisticated as those used for space exploration, rely only little on new research in basic physics or on the discovery of new laws. They are mostly based on applications of well known laws and of techniques developed some time ago. People who do basic physics research, particularly in technologically developed countries such as the US, now often find themselves having to *oppose* new plans for large-scale technological "advance," whether it be a widely deployed antiballistic missile system, excavation with nuclear devices, or

"not only to know how nature is and how her transactions are carried through, but also to reach as far as

a supersonic transport. These are gadgets that, in the opinion of many physicists, have more long-range dangers than benefits.

The connection between basic research in physics and technical advance is, contrary to folklore, generally indirect or roundabout. Only rarely is a basic advance made consciously as a prelude to a major technical improvement. The physicist Hendrik B. G. Casimir illustrated this proposition with examples of technological progress that resulted from the work of scientists who had no well defined practical aims:

"One might ask whether basic circuits in computers might have been found by people who wanted to build computers. As it happens, they were discovered in the 1930's by physicists dealing with the counting of nuclear particles because they were interested in nuclear physics . . ."

"One might ask whether there would be nuclear power because people wanted new power sources, or whether the urge to have new power would have led to the discovery of the nucleus. Only it didn't happen that way, and there were the Curies and Rutherford, and Fermi, and a few others . . ."

"One might ask even whether induction coils in motorcars might have been made by enterprises which wanted to make motor transport, and whether then they would have stumbled on the laws of induction. But the laws of induction had been found by Faraday many decades before that . . ."

"Or whether, in an urge to provide better communication, one might have found electromagnetic waves. They weren't found that way. They were found by Hertz who emphasized the beauty of physics and who based his work on the theoretical considerations of Maxwell. I think there is hardly any example of twentieth-

century innovation which is not indebted in this way to basic scientific thought."³

All this history of indirection does not mean that a developing nation should not pursue applied research strongly, nor that basic-research scientists should not be associated with mission-oriented laboratories. But one must not raise too many false hopes. I believe that the 19th-century faith that science will show the way to the solution of all problems and lead us soon to Utopia was a tragically naive illusion; now that it is clear that no amount of scientific progress will quickly remove such dangers as racism or nuclear blackmail, we are reaping the results of a backlash.

There is a second reason it is wrong to seek relevance for science only in the immediate benefits to technology. Not only have technological advances, all too often, brought with them major social problems as unforeseen byproducts, but also these problems can not be cured or even properly understood through existing scientific, technological or political means alone. Such cures, rather, depend to a large extent on new, basic advances, not least on advances in science itself. At the heart of social problems created by technological advance is the *absence* of some specific basic scientific knowledge. This realization gives a whole new mandate to basic scientific research.

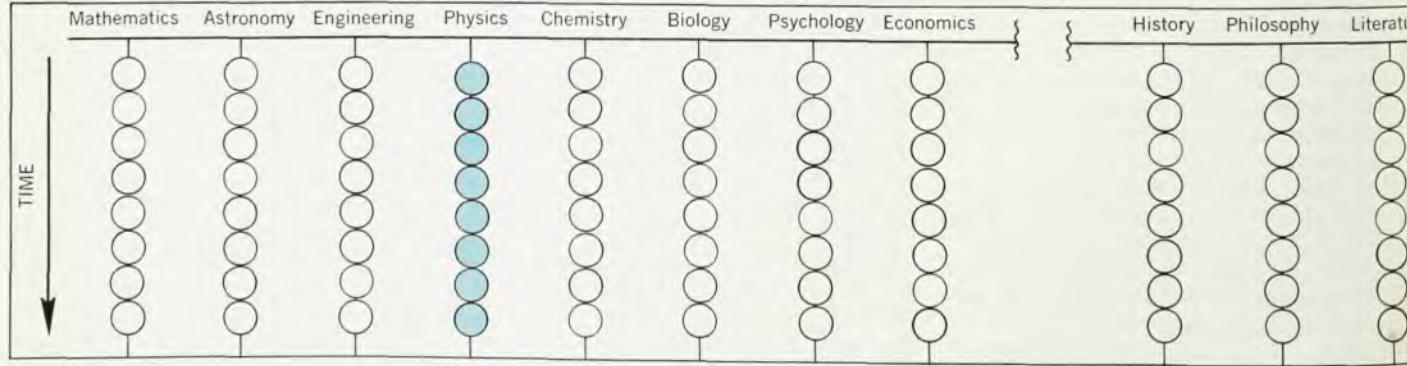
Examples come readily to mind. It is quite customary, for instance, to say that the population explosion is in part caused by the advance of medical science (better sanitation, inoculation, antibiotics). But one can equally well claim that the population explosion is bound to overwhelm us precisely because we do not yet have at hand sufficient knowledge in pure science. That is to say, the complex problem of overpopulation is due in a large degree to our current (and long acknowledged) ignorance of the basic process of conception—its biophysics, biochemistry and physiology. No wonder that attempts at controlling population are

so halting. What is astonishing, rather, is that the first medical-school laboratory in the US specifically designed to study the whole range of scientific problems in the process of reproduction is only now being built.

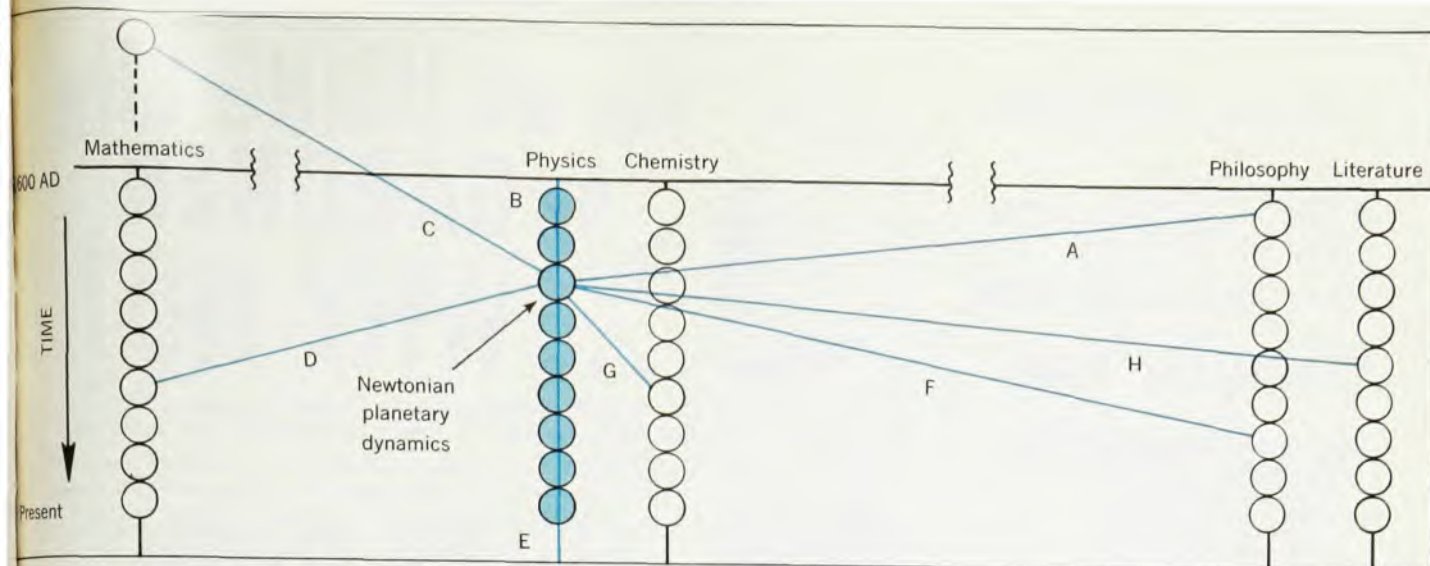
Similarly, it is sometimes said that progress in physics is "responsible" for the threatening arms race. But it is more accurate to say that nuclear arms-control treaties are difficult to achieve largely because insufficient knowledge of geophysics makes inspection of suspected, illegal weapons tests with seismographs difficult. A better understanding of geophysics, it turns out, will be needed before some nations will consider it safe to enter arms-control treaties that outlaw underground weapons tests.

The problem of bringing food to hungry people in arid lands near the sea, as in Peru, India or the United Arab Republic, is to a large extent one of logistics and management. But it is also a problem of basic science: Before we can design more economical desalination plants, we need a more fundamental understanding of liquid structure (one of the old but much neglected problems in physics and chemistry) and of flow through membranes. Pollution is, of course, a result of greed, stupidity, apathy and lack of law enforcement. But to clean smog-ridden areas more effectively will require greater basic knowledge than we now have of meteorology and of the physics and chemistry of combustion. And, in the meantime, to this day the most effective and insufficiently used device for getting rid of pollution by solid particles is the electrostatic precipitator, which essentially works on scientific principles known since 1600.

These observations serve to oppose two widely current but erroneous notions: First, that basic science is an unnecessary luxury and should be supported only if it is directed to immediate practical applicability (as the quotation by Casimir above indicates, things just don't happen that way), and second, that one way of stopping the



In a traditional course, we often teach physics as if it were separate and independent, like a string of beads. Figure 1



Newtonian dynamics is linked to past and present achievements, not only in physics but in other fields as well. Figure 2

abuses that are byproducts of technical innovation is to stop science (whereas in fact curing existing abuses often depends on scientific advances yet to be made).

Long-range social benefits

Turning from the immediate to the long-range effects of science that give it relevance, we see ample evidence that every person now alive, whether or not he has studied science, is intellectually a child of Copernicus and Galileo, Isaac Newton and Faraday, Einstein and Niels Bohr. Our imagination and intellectual tools were indeed largely shaped by the advances in the knowledge of physics they and their contemporaries made long ago. It is easy to show that, when the Copernican and Newtonian worldview triumphed in the West, the recognition that a uniform law holds sway over all matter everywhere helped to overcome hierarchical thinking and to prepare the mind for self-reliant democracy. We know also that in the 19th century the successes of statistics and of the concepts of energy prepared the ground for modernization of the Newtonian worldview.

In addition to the kind of long-range influence that Newton's work had on the imagination of writers and philosophers from the 18th century on, there are also the more material long-range effects associated with the advances made by James Watt, Faraday and Fermi. From an understanding of how the steam engine works flowed a century-long transformation of society which is now studied as the "Industrial Revolution." From Faraday's "toys" came electric motors and generators and, in time, the electric-powered elevators, trains and subways that facilitated the upward and sideways growth of cities. Similarly, the experiments of

Fermi's group on neutron-induced artificial radioactivity prepared for the study of nuclear fission, and this in turn led to the design of new energy sources that may well be the chief means for meeting our frantically growing energy needs.

It is of course even more difficult to foresee the long-range effects of science upon social change than it is to see the immediate practical influences. To avoid possible negative effects and to capitalize on positive ones, there is only one policy available to us: the exertion of uncompromising watchfulness as both citizens and scientists. We must call attention to existing abuses of scientific knowledge or skills and keep up-to-date on scientific advance so as to be ready to keep science from being detailed and abused in the future.

A study related to all others

The fourth meaning of "relevance" refers to science not as merely a technical study but as a part of the general humanistic development of mankind. We agree fully with I. I. Rabi who noted that

"Science should be taught, at whatever level, from the lowest to the highest, in the humanistic way. By which I mean it should be taught with a certain historical understanding, with a social understanding and a human understanding, in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations."⁴

We can illustrate the need for this sense of humanistic interconnectedness with two simple diagrams. The physics course, as traditionally given in many classrooms is like a string of beads.

One subject follows another, from Galileo's kinematics to the most recent advances in nuclear physics. This sequence is the usual one, which more or less parallels the historical development of the science, whether this parallel is made explicit or not. But few if any connections are shown with achievements of human beings who are not physicists, with sciences other than physics or with studies and activities other than science. And all too often the materials studied in the other courses (for example in chemistry, in biology, in literature) also hang like so many separate strings of beads (see figure 1).

There are some advantages in such a string-of-beads presentation. It is, for example, convenient to teach. But ignoring connections that do exist among all these fields does not do justice to the actual state of affairs. A research project in experimental physics, for example, sooner or later draws on material not only from almost every part of a physics curriculum but also from mathematics, metallurgy, chemical thermodynamics, electronic engineering, computer technology and many other sciences, as well as group psychology, accounting and skill in writing about the work. Moreover, nobody who has engaged in actual scientific work can fail to see the influence that scientific advances can have in terms of social and practical consequences. "Pure" physics is an invention that exists only in the most old-fashioned classrooms. If you pick up a real problem in physics (or any other science), there extends from it connections to a number of expected and unexpected problems that at first glance seem to "belong" to other professions.

I believe this is one argument in favor of including occasionally in a physics course topics not usually re-

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ferred to. Think back, for example, to the study of Newtonian mechanics as applied to planetary motion, a subject that is usually one of the "beads" on the physics chain. Newton had studied theology and philosophy, and those ideas emerge in the *Principia* in his sections about the nature of time and space (see figure 2, link A to philosophy). Within physics itself, Newton brought to a culmination the work of Kepler and Galileo (link B). Much of the established mathematics in Newton's work came from the Greeks (link C). New mathematics, particularly the basic ideas of calculus, were invented by Newton to aid his own progress, thereby advancing the progress of mathematics (link D).

Within physics, all who follow Newton will use his laws and approach (link E). His effects on the Deist theologians (link F), on John Dalton's atomic models in chemistry (link G), and on the artistic sensibilities of the 18th century in which Newton swayed the muses (link H) are quite easily documented.

The same kind of web extends around each of the chief topics of physics (as indicated in sections of the Project Physics Course). Think of the link from philosophy to the work of Hans Christian Oersted, André Ampère, and Faraday in electricity (through their interest in *Naturphilosophie*). Think of the link reaching from nuclear physics back along the chain to the classical physics of three centuries earlier (as in the determination of the neutron mass) and of the sideways links to biology, to engineering and indeed to politics, owing to the various applications and byproducts of nuclear reactors, for example.

Such links exist between main achievements in many fields. Some of the topics and persons, discussed in a physics course that perhaps only briefly but at least honestly draws attention to this state of affairs will also come up in other courses the student will be taking. If we drew all the links between fields on the intellectual map, we would see instead of separate strings of beads a tapestry, a fabric of ideas. This view of the relevance of science should deeply penetrate a physics course that intends to educate as well as to train. Science is then seen to be in dynamic interaction with the total intellectual activity of an age. In a deep sense, science is part of the study of history and of philosophy, and it may underlie the work of the artist, just as it penetrates into the explanation a mother gives to her child to help him understand the way things move.

If we therefore tried to think away the achievements of physics, the course of modern history would be almost incomprehensible. We could not under-

stand, and in fact would not have had, much of the work of John Locke, Voltaire and Alexander Pope, men who, among many others, were frankly inspired by the work of physicist contemporaries. Conversely philosophy, mathematics, and other fields would be far emptier studies without their fulfillment and extension through the work of philosopher-scientists such as Ernst Mach, Einstein and Bohr. Eliminating physics would, of course, also make nonsense of the history of industrial development following Watt's steam engine, Alessandro Volta's electric battery and Faraday's motors and generators. A neighboring science such as chemistry could not have developed without the models of gases and the theories of atomic structure that were largely the work of physicists. In short, if you pull the thread marked "physics" from the tapestry—as some antiscientific persons wish to do—the whole fabric would unravel as an old sweater does; the same would be true if any of the other threads were pulled. In this view, therefore, the relevance of any field of knowledge, including science, is that it is an integral part of the total growth of thought.

All too often students have to discover the fabric of ideas for themselves. For it is a bad (though well rewarded) habit of some academics to teach their own subject as if it had nothing to do with others. It is precisely by seeing the connections between fields, however, that one becomes educated. We should make some of these links explicit in our courses in the hope of providing an educational experience that the student should ideally find in his other courses as well.

Science as a style of life

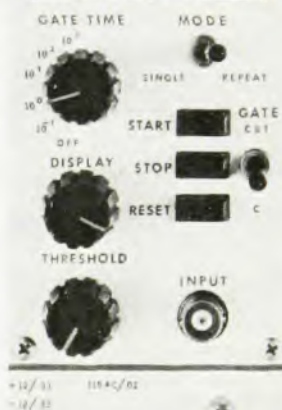
Modern science is not an élite enterprise for only a self-selected few there are now millions of men and women engaged in it. In the US alone there are nearly 50 000 people who contribute to physics, each in his own way. Some prefer to follow their thoughts entirely alone, some are surrounded by students or collaborate with groups of colleagues. Some are in small university laboratories, some in large industrial enterprises. Some accentuate the sober rationality and objectivity that it is possible to achieve in scientific work, others pursue their work with a passion and a daring that makes one dizzy. Some are veritable saints, and others are not; possession of knowledge does not itself necessarily convey virtue. Some have no academic degree at all, others are laden with diplomas. What they share is a style of life and a way of looking at the world; this style gives science additional relevance and has a number of earmarks or components.

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One "minority" group that has been of particular concern to scientists is that made up of young people. A whole set of social inventions and devices operates in the life of science to recognize and reward talent as early as possible. The young scientist is welcome and is brought as quickly as possible to participate at the growing edge of new science. As a team member he may be an expert in some subject, teaching those who are his seniors. And unlike the situation in many other disciplines, it is widely recognized in science that a person may make his most imaginative contributions while still young.

To complete these comments about science as a style of life, we note that scientists have increasingly recognized that discovery of new knowledge and the teaching of established knowledge are not their only responsibilities. Rather, scientists are prominent among those who take part in examining the immediate social consequences of scientific and technical advance. Their knowledge of science adds to their obligations of citizenship. We see therefore that there can be a happy complementarity between taking part in developing the human values of society and taking part in the growth of science. Most also agree that science and its technological offspring must come under the control of an anthropocentric ethic if man is to survive. There need not be a polarization between science on the one hand and a rational humanism on the other; on the contrary, these two approaches to the world sustain each other.

Perhaps more than many other professionals, the humanistically aware and responsive scientist should therefore be counted on to do his share to aid mankind in its many current distresses. It is up to us, as scientists, teachers or administrators, to fashion courses in which these points are made and in which the growing young person, whether prospective scientist or not, can experience this relevance.

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This article is adapted from a talk given by the author last June in Srinagar, India at the US-India Conference on Physics Education, sponsored jointly by the US and Indian governments. The material is based on the epilogue to the Project Physics text. □

in the world of nature. It makes sense to them, and they are comfortable with it, although knowing full well that the most surprising and important findings are still in the future. To physicists the world is not a succession of incoherent, unique events. Even partial knowledge about nature gives a person a sense of the relations between phenomena—the way in which the world hangs together in a rational and ecological manner. Such knowledge does not, however, "explain away" the phenomena or dull the excitement about them any more than knowing the rules of football makes you less involved in watching the game. Of course nobody knows a fraction of all there is to know even in a single one of the sciences. But still, one can feel quite at home in a city, even if one has personally walked through only a few percent of all its streets; if you know the pattern in outline and the crucial details of some regions within it, you no longer feel a stranger. Perhaps this explains the confidence and optimism characteristic of many good scientists.

We have stressed the intellectual interest in science for society as a whole, but there is also a personal aspect for every scientist or student: Here is a chance to devote one's professional life to something one loves to do. Those who select a science as a career, and who are at all good at it, are on a road through a changing landscape along which each can select his own problems to work on. Being a scientist can be a way of spending one's professional life, day by day, in what one likes to do and is doing well. It is not like reading a play or watching it, but like writing it and acting in it. And much of the same satisfaction goes to those who spend most of their lives not as research scientists but as teachers, in high school or college, and who have found that their chief satisfaction is helping young people to realize what role science can play in their lives.

Each profession has its own values, and the values of day-by-day life in science can and should be illustrated in our courses. Values of this kind that come to mind include free inquiry and free publication, perseverance and objectivity, the satisfaction of honest intellectual effort and optimism about Man's ability to understand nature and put it to good use. Nowhere more than in science is intellectual merit and skill honored. No matter who or what he is, the scientist is taken seriously by his peers for what he can do. Consequently, some minority groups have broken through social obstacles more easily after first receiving recognition for their excellence in scientific work. There is in science a great amount of room at the top, as well as an atmosphere of belonging to an effective, in-