Reshaping the image of physics

Too many students visualize physics merely as a collection of laws and equations. Teachers should communicate as well some of the excitement, beauty and uncertainty of the subject.

John S. Rigden

Most students have a jaded image of the individuals who call themselves "physicists" and of the subject called "physics." This regrettable state of affairs has arisen primarily because of the manner in which we present physics to our students, particularly to our beginning students. At present the wonder, the excitement, the awe and the enthusiasm of the physicist is too often missing. The intrinsic beauty of physics, its humanistic dimension and its inherent limitations are seldom part of our classroom fare and are unknown to the student.

To change the image we must change our style of teaching. We should emphasize the "verb" sense of the subject (physics as a dynamic discipline) as well as the "noun" sense (physics as a collection of laws, definitions, formulas). Also we should reduce the element of dogmatism that is all too often present and teach instead some of the inherent limitations. And to make space for these changes we will have to reduce the quantity of material presented.

The image of physics

To most students, a physicist can be symbolized by a brain suspended in saline solution. Translated, this means the physicist is exceedingly bright (perhaps frighteningly so), but isolated from his social environment and quite uninteresting. In other words, he is a brilliant bore.

Margaret Mead and Rhoda Metraux[1] have employed professional strategies in determining the high-school student's image of the scientist. David Beardslee and Donald O'Dowd[2] have done the same for the college student. Mead and Metraux find the high schoolers saying: "The scientist is a brain. He spends his day indoors, sitting in a laboratory, pouring things from one test tube to another. His work is uninteresting, dull, monotonous, tedious, time consuming, and, though he works for years, he may see no results or may fail . . . He is so involved in his work that he doesn't know what is going on in the world. He has no other interests and neglects his body for his mind. He can only talk, eat, breathe, and sleep science." Beardslee and O'Dowd find the college students describing the scientist as "unsociable, introverted, and possessing few, if any, friends."

Students also have a strange image of physics. I remember well a conversation I had several years ago with a book salesman. He represented a house that publishes an extensive line of excellent physics books. Something in our conversation prompted me to ask him: "What is physics? What do you think of when you think about physics?" The salesman was speechless and he remained so for at least thirty seconds. Finally, after considerable effort, the essence of physics jelled in his mind. "A pulley," he said, "when I think of physics I think of a pulley." Now I was speechless. After a moment I added, "Yes, and if you think for another thirty seconds you'll undoubtedly remember the inclined plane." "Right!", the salesman exclaimed proudly, "A pulley and an inclined plane."

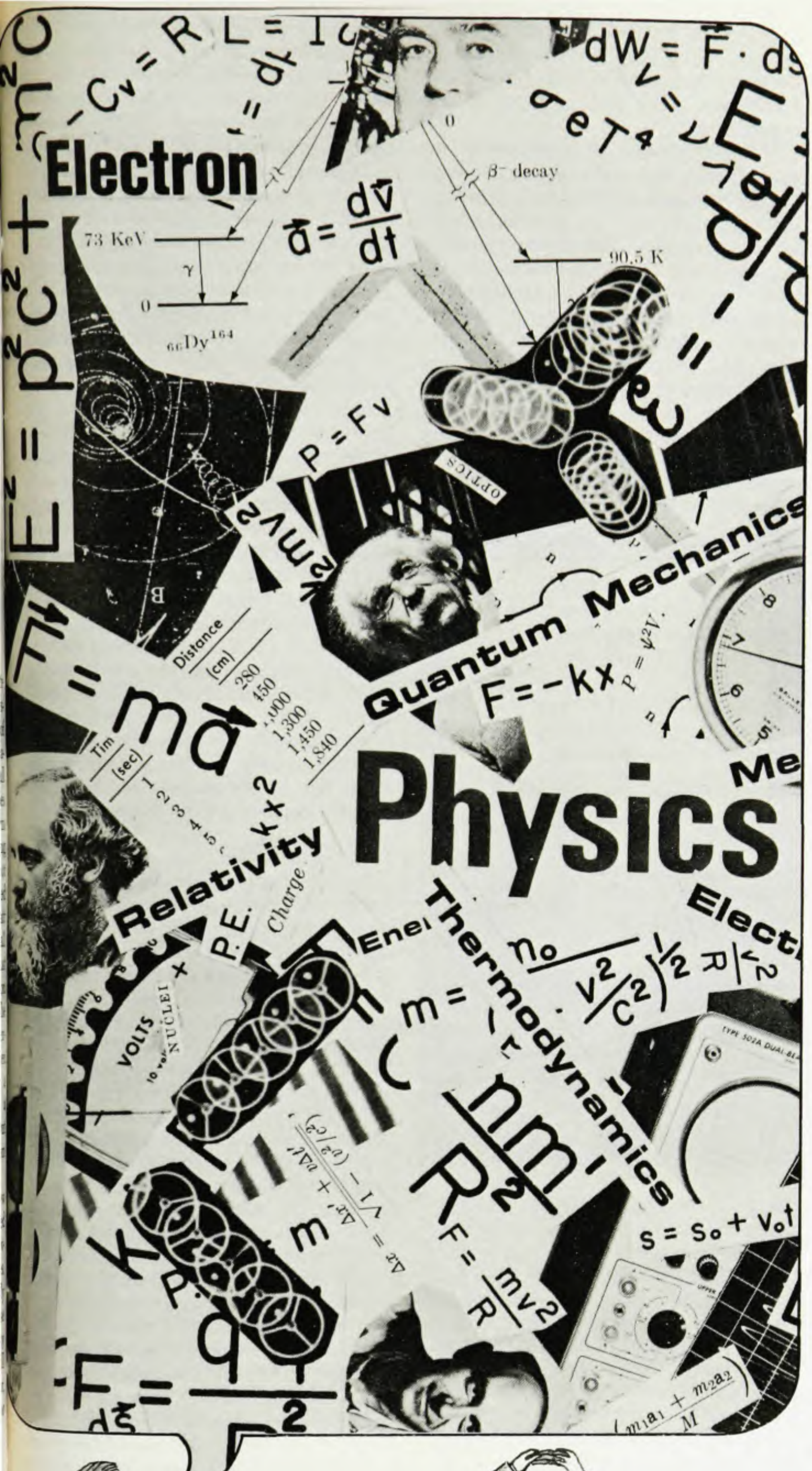
Did this salesman ever have a course in physics? Or, did he ever talk with students who did? The answer to both questions is "yes." It is unfortunate that many students complete our physics courses—with good grades, some of them—and yet have a completely fallacious concept of what physics is all about. When Richard Feynman cites the fun and enjoyment people get from "reading and learning and thinking about it,"[3] the pronoun "it" does not refer to either a pulley or an inclined plane. Likewise, when John Platt says[4]: "Only physicists and baseball players get paid for doing exactly what they want to do," he does not envision pulleys and inclined planes taking the place of baseballs and bats. The American Institute of Physics has chosen Platt's statement for the lead line in a promotional document "Physics as a Career." Students must wonder about a profession that gets its thrills from something as insipid as a pulley.

Fortunately, the developers of new physics curricula have quietly dropped much of the content traditionally covered in beginning-physics courses. Among the discards you will probably find the pulley. But the style of these new curricula remains the same in many essential aspects. Future salesmen will not remember pulleys and levers; rather, they will recall the harmonic oscillator and "inertial frame."

Noun and verb sense

What is physics? This question is asked directly or alluded to in the early pages of most introductory physics texts. The question is usually evaded, and a "wait-and-see" attitude is adopted. Thereupon the student is thrust into the subject matter, and a personal image of physics begins to evolve. After the nine-month gestation period the image

John S. Rigden is an associate professor of physics at the St Louis campus of the University of Missouri.



is fully formed in the mind of the student. It is usually a lackluster image with a myriad of concepts and formulas blurred into one another. It takes on personal significance for each student as specific features protrude from the blurred background: a pulley here, a vector there, Ohm's law, and . . . oh yes, the sliderule.

In answering the question "What is physics?" we must consider physics in both its noun and verb senses. The substantive content of physics as it is now known constitutes the noun sense. It begins with such basic concepts as space, time, matter, charge, energy, field and entropy. Around these concepts the subject is organized in such a manner that an internal structure appears. Classical mechanics is formed around such concepts as space, time and energy, with motion as its principal feature. The concepts of charge and field are central to electromagnetism. Classical mechanics and electromagnetism, along with thermodynamics, relativity and quantum mechanics, are chief structural elements that give physics its identity.

Each structural element abounds in fine details—so much so, that the student often fails to relate the details to the gross structure. Among this detail there are definitions to facilitate expression, for example, acceleration, momentum, calorie, resistivity, inertial reference frame, and so on. There are a large number of definitions.

At a more abstract level, there are relationships between defined quantities. Force and momentum are related, and so are invariance and inertial reference frames. Some of these relationships are represented symbolically, and the students call them "formulas." There are many, many formulas. The most important relationships are called "laws": Newton's laws, Ampere's law, the thermodynamic laws, Snell's laws. The list is long. The concepts, definitions, relationships and laws comprise the formal noun sense.

There is also a practical noun sense. It is sometimes difficult, particularly for beginning students, to distinguish between physics and the devices used in physics. What starts as a means to an end becomes an end in itself and assumes an identity as an integral part of the subject. I have already mentioned the pulley and the inclined plane. Other "things" can be included: slide-rule, simple pendulum, ammeter, thermocouple, Wheatstone bridge, transistor and oscilloscope.

The noun sense of physics so far described can be likened to a photographic snapshot. A snapshot can be attractive; however, more often than not it is merely factual. It is all-inclusive and indiscriminate. Occasionally an interpretive rendition of the noun sense of physics is given. In these cases beauty emerges, and the metaphor needs to be changed from a photographic snapshot to an oil painting. The identity of the "artist" becomes important, and we have, for example, *Physics* by Feynman, *The Fabric of the Atom* by Philip Morrison and, in a somewhat different vein, Banesh Hoffmann's *The Strange Story of the Quantum*.

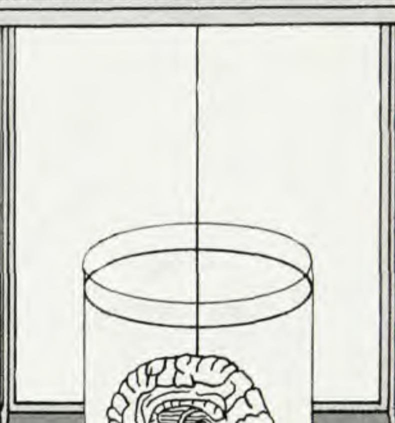
In an interpretive rendition of physics, a physicist can bring out in sharp contrast those themes or features of the noun sense that excite him the most. He might choose to emphasize the scope of physical law—from atoms to galaxies. Or perhaps he sees the unity of structure and hence the simplicity of physics. It might be the conservation laws with their implied symmetries, or then again it might be the parsimony of nature with just four basic interactions providing the rich variety we observe. Indeed, the noun sense can be beautiful and exciting.

There is one additional similarity between the noun sense of physics and either the photographic snapshot or the oil painting. Like the snapshot and the painting, the noun sense of physics is *static*.

A cryptic definition of physics is frequently given: Physics is what physicists do. This definition reflects the verb sense of the subject. Extending our metaphor, the verb sense can be likened to a motion picture. A time-lapsed sequence of frames, each individually interesting, reveals something no single frame can disclose. Taken together, they show a trail, rarely straight and smooth, more often meandering and tortuous, from an emotion of fear and superstition to an attitude of "at homeness" in our natural environment. Together they show an evolution of thought as understanding begets new knowledge. The verb sense of physics is *dynamic*.

When the physicist manipulates nature to learn its secrets, he is participating in an ongoing adventure similar in many respects to the exciting adventures of a sleuth. The physicist is seeking the clues among a rich variety of facts that will enable him to unravel a small part of the mystery of nature. The great physicists are those who produce new hypotheses, and in so doing revolutionize the way men understand nature.

These integrating explanations are



the great theories of physics and form a notable part of its verb sense (as well as part of its noun sense). They form the basis for planning and decision making. Experiments are designed to challenge the theories at their weakest points and to extend them to new extremes. Karl Popper has said,[5] "Theories are nets cast to catch what we call 'the world': to rationalize, to explain, and to master it. We endeavor to make the mesh ever finer and finer."

Einstein recognizes both the end of science (knowledge, or our noun sense) and the means (theory), when he emphasizes that science must start with facts and end with facts, no matter what theoretical structures it builds in between. This back-and-forth between fact and theory, this dynamic interplay, is a decisive part of the verb sense of physics and provides the adventure that captivates the mind of the physicist and rewards him with thrills and excitement.

Many episodes illustrate this feature of the verb sense. One begins in 1820. A French astronomer, Alexis Bouvard (who remembers him?), was engrossed in his study of the three outer planets: Jupiter, Saturn, and Uranus. An analysis of the recorded positions of Uranus made by a deceased colleague led Bouvard to the surprising conclusion that Uranus was not where it should have been. A small discrepancy existed between predicted and actual location. By 1832 it was clear: Uranus was misbehaving. Two mathematicians, Cambridge undergraduate John Adams and Jean Leverrier of the Ecole Polytechnique, independently showed by theoretical calculations that the discrepancy could be accounted for by the presence of still another planet. With the results of Leverrier's analysis in hand, the Berlin Observatory quickly located the new planet. The year was 1846. The planet was named "Neptune."

The full cycle of physics is fact to fact via theory. Physics starts in the noun sense and finishes in the noun sense. Both the start and the finish are beautiful and even awe-inspiring. But the intrigue, the drama, and the excitement lies in the pursuit of the finish. And the pursuit is the verb sense.

Style in teaching

If the image of physics is to be remade, our style of physics teaching must be changed. At present we overemphasize that aspect of the noun sense I have compared to the photographic snapshot. We make definitions, introduce concepts, derive relationships and contrive problems at such a prodigious pace that our students have likened their physics courses to drinking from a fire-hose. Students grasp at these definitions and formulas as the essence of the subject. One experienced teacher, Polykarp Kusch, has commented[6]:

> "The scrupulously honest student will commonly memorize formulae till just before he enters the examination room and then, as the examination starts, will write in his examination book a string of formulae, preferably in the upper right-hand corner of the first page. The student casts about for some formula which may conceivably fit the problem; sometimes, by some magic, it does . . . This is part of an ineradicable belief that physical science is, in essence, an assemblage of formulae."

Three changes in our style of teaching are necessary if we are going to alter the "ineradicable belief that physical science is, in essence, an assemblage of formulae" and at the same time reshape the image of physics.

First, the harshness and sterility of the snapshot aspect needs to be mellowed and adorned by the oil-painting aspect. Physicists share with the poet and artist the enchantment of immediate empirical experience. But, whereas the artist gives vent to his wonder with an imaginative juxtaposition of words or slashes of color, the physicist's response to nature's delights is too often that of a stodgy pedant.

Loren Eiseley laments[7] not only the reluctance of scientists to express their sense of wonder at nature's beauties, but also the response of members of the scientific fraternity when such expressions are given:

"Our faith in science has become so great that though the open-ended and novelty-producing aspect of nature is scientifically recognized in the physics and biology of our time, there is often a reluctance to give voice to it in other than professional jargon . . . I have had the experience of being labeled by that vague word "mystic," because I have not been able to shut out wonder occasionally, when I have looked at the world."

Scientists claim to have built an intellectual structure that can inspire both interest and pleasure—a structure worthy of the effort required to appreciate it. If our students are to believe this claim, we must occasionally share the noun sense of science in the language of the heart.

Second, our teaching must be more faithful in presenting the verb sense. Facts, baldly stated, are usually uninteresting. But the same facts placed within the context of how they came to be understood can become fascinating and perhaps even exciting.

I remember an occasion when a group of students were casually told that the nuclear spin of sodium is 3/2, and they have never forgotten it. Victor W. Cohen of Brookhaven National Laboratory was a Visiting Scientist on our campus in 1963. During his visit he recounted the early days of Isidor Rabi's laboratory where the resonance technique was developed. He talked not only about the physics of the resonance method, but also about the environment in which this technique, which ultimately brought Rabi the Nobel Prize in physics, was perfected. Early one morning, as most of New York slept, Cohen completed one of the first experiments with this newly developed experimental tool—and with unequivocal results. It was still dark when he left the Columbia lab and started home. Only a few people were on the subway at that early hour, but Cohen looked at them all and felt the thrill and elation of being the only one who knew the result of the experiment just completed: He knew the nuclear spin of sodium to be 3/2.

Several of the students who heard Cohen's account were college sophomores. Two years later, near the end of their senior year, I asked a group of these students to recall for me some of the highlights of their college years. I was surprised. One, now a graduate student at the University of Chicago, said he would never forget the story of Cohen's early-morning subway ride content in his knowledge—his *sole* knowledge—of the nuclear spin of sodium. As I looked around the group of seniors, several were nodding their heads in agreement.

There is a postscript to this story. In 1967 I told Rabi about Cohen's narrative and about the student's reaction to it. Even as I talked, a sense of exuberance seemed to come over Rabi, and his eyes sparkled. He began to reminisce

about those action-packed days and the excitement that was generated as the resonance method proved itself repeatedly with noteworthy results. He told about his students working for long periods with little or no "time off." No one wanted time off. He told how Norman Ramsey initiated a lunchtime seminar where physics was debated over brown-paper bags. As Rabi continued to talk his excitement was contagious. Furthermore, his comments contained the essence of science that he himself[8] has aptly expressed elsewhere: "Our goal is a sort of bootstrap operation to utilize the tools of present knowledge to gain new knowledge, knowledge which we could hardly have foreseen or imagined."

This bootstrap operation is the verb sense of physics, and this aspect is curiously and sadly absent in our physics courses. For some reason we have adopted the attitude that there is a deep cleavage between objective knowledge and the pursuit of that knowledge. Max Born has pointed out that any notion of the separateness of objective knowledge and its pursuit has been destroyed by physics itself. With the absence of the verb sense, we present a distortion—a sterile version of physics unable to reproduce itself.

The verb sense must become an integral part of our courses. It will be very difficult and perhaps even impossible to communicate effectively to the beginning student the more intriguing and far-reaching aspects of contemporary physics. This is indeed unfortunate; however, the impossibility of sharing today's physics with today's student is neither necessary nor sufficient reason to omit the verb sense of the subject altogether. There are alternatives. For example, certain topics can be developed historically in such a way that much of the drama and intrigue can be created anew for the student. The historical development of selected topics, perhaps as case studies, would show the student how ideas are born, tested, modified, compressed, integrated into more general schemes, or devitalized to the extent that they slowly fade from the scene.

There is still another misconception about science that might be corrected by a greater emphasis on the verb sense. The misconception I refer to is the view of science as the all powerful, final authority. The teachers of science in the elementary grades, in the high schools, and in the colleges are too often responsible for originating and perpetuating this image of science as the savior of mankind. The teachers, however, are abetted in this distortion by textbooks that are overwhelmingly taken up with the noun sense of science and in which the subject is presented in *fait accompli* fashion.

Science is not free of dogmatic thought and must constantly guard against it. In his dialogues, Alfred North Whitehead speaks[9] of the personal trauma that resulted from the revolutions in physics that occurred early in this century: "I have been fooled once, and I'll be damned if I'll be fooled again. Einstein is supposed to have made an epochal discovery. I am respectful and interested, but also skeptical. There is no more reason to suppose that Einstein's relativity is anything final than Newton's *Principia*. The danger is dogmatic thought; it plays the devil with religion, and science is not immune from it."

Alfred Landé warns[10] against the policy: ". . . if you cannot explain it, call it a principle; then defend it as fundamental and absolutely irreducible, so that speaking of the unsolved riddle

from here on becomes the mark of naiveté if not of heresy." E. Bright Wilson has recently issued a note of caution to chemists[11] about the very thing Landé warns against.

One remedy for both the dogmatism and the savior image of science is a study of the history of science. Such a study, even if it is rather superficial, will make a mockery of dogmatism and will establish how science has "backed and filled," advanced and retreated. For example, let us look again at the discovery of Neptune. Earlier I used this discovery as an illustration of the noun aspect of both the beginning and the ending of scientific investigation; however, to make the intended point I dangerously oversimplified the episode. There was *not* a straight-line progression from the discrepancy of Uranus' position to the discovery of the eighth planet. Between the beginning and ending we have:

- abortive attempts to fit the observed positions of Uranus to an elliptical orbit
- the development of powerful analytical methods by Karl Friedrich Gauss for the computation of planetary orbits
- Alexis Bouvard charging four respected and reliable astronomers of making enormous experimental errors (as large as 1000 per cent) in his attempt at finding an elliptical orbit for Uranus
- five competing hypotheses to explain the discrepancy in predicted and observed positions of Uranus with prestigious proponents of each (George Biddell Airy, England's Astronomer Royal, 1835–81, believed the discrepancy was "from a failure in the law of gravitation")
- the Plumian Professor of Astronomy and director of Cambridge University Observatory, James Challis (1803–1882) missing the honor of discovering Neptune because it was "so novel a thing to undertake observations in reliance upon merely theoretical observations"
- an international dispute over the priority of the discovery.

A greater emphasis of the verb sense of science in the form of developing some topics historically offers clear advantages.

The third change in teaching style required to reshape the image of physics can be regarded as a consequence of the previous two. Simply stated, the quantity of material must be reduced. Obviously, something must give if the teacher is going to find time to share his sense of wonder at the beauties he sees in the intellectual structure called "physics," developing those themes that excite him, and also to show how today's verb sense determines tomorrow's noun sense by tracing the evolution of selected concepts. However, the need to reduce the quantity of material customarily presented to beginning students need not be regarded as a consequence of anything. There is simply too much. One cannot drink deeply at the fountain of knowledge via a "firehose." When a student is confronted weekly with a huge quantity of material, he gives his attention to only the most salient features. He will remember (only as long as necessary) $\mathbf{s} = 1/2\mathbf{a}t^2$, $\mathbf{F} = m\mathbf{a}$, $T = 1/2mv^2$, and so on; if, for example, he is given $\mathbf{F}$ and m, he will dutifully solve for the $\mathbf{a}$. So, in the rush of things, physics becomes identified with these most salient features and, to the student, physics is $\mathbf{s} = 1/2\mathbf{a}t^2$, $\mathbf{F} = m\mathbf{a}$, ...

This distortion of physics is a tragedy. The extent of the tragedy becomes apparent if a student is asked to write a brief essay on any one of the above formulas, for example $\mathbf{F} = m\mathbf{a}$. Ask the student to write:

- one paragraph about each concept the symbols $\mathbf{F}$, m, and $\mathbf{a}$ represent
- a paragraph about the equals sign (Is $\mathbf{F}$ always equal to $m\mathbf{a}$? As $\mathbf{F}$ is characteristic of a particle's environment, whereas $m\mathbf{a}$ is characteristic of the particle itself, is not the equals sign somewhat startling?)
- a paragraph about the formula in its entirety–its range of applicability, its place in physical theory, its vector nature.

That is a five-paragraph essay. You

might ask for a sixth paragraph—extra credit—in which the student is asked to supply some background to the formula $\mathbf{F} = ma$: How did we come to believe it? Were men surprised to find that $a \propto \mathbf{F}$? Does $\mathbf{F} = ma$ follow from common sense?

The new physics curricula developed in recent years are laudable in many ways; however, the density of concepts is still prohibitively high. Although many topics have been dropped (examples are sound, calorimetry, machines, strength of materials, optical devices), new topics have replaced them (special relativity, quantum theory, nuclear physics, atomic structure, elementary particles). The introductory physics course remains, even in the newer versions, an attempt to confront the student with the totality of the subject. And the style in which the introductory course is taught has not changed.

A humanistic enterprise

I have proposed three changes in our style of teaching. These changes are directed towards correcting the distorted image that many students have of science. The gist of these changes can be succinctly summarized: Bring humanity back into science. To have sensations of wonder, humility, awe, bewilderment and excitement, and to give expression to them, is characteristically human. To place greater emphasis on the verb sense of science is to bring greater attention to bear on the human dimension.

It is timely to make these changes. Science has had an advantage over some disciplines in that society has handsomely rewarded the services of scientists. Thus, regardless of the hurdles we teachers of science have created for the aspiring scientist, our success was assured. Recruiters from industry, government, and academia, grouped at the finish line of the academic obstacle course with their high salaries and prestigious positions, have provided the needed motivation to start and finish the race. Now, however, the situation is changing. We are increasingly dealing with the children of an affluent society. Many of these young people have grown up with enough, if not plenty, and their values have been rearranged. The dream of material plenty is essentially within the grasp of all, yet, because we often seem to be paying for progress in the currency of human values, the appeal of material blessings is waning.

With disturbing frequency we are hearing the charge from student lips that science is irrelevant. This charge stems in part from the pulley-and-inclined-plane image of science. But the roots of this charge also spring from our students' keen sensitivity to the human dimension in all academic pursuits and, more generally, to their concern about the quality of life in our society. Students are increasingly viewing science in terms of human values and in terms of its relation to society.

Eugene Rabinowitch appears to recognize the new awareness of students when he issues[12] this challenge:

> "The central problem of higher education is how to bring up new generations, fit to live as individuals and as citizens. The changing habitat which science is creating for them involves not only education in science, but perhaps even more importantly, education about science—the development of understanding of what science is about; what it can (and what it cannot) do; appreciation of the role of science in past history and its likely role in the future; of how its revolutionary force can be best used in the framework of a stable democratic society . . . ."

This challenge can be met by a change in teaching style. Nature is always miraculous in its originality. To understand a bit of this wonder is the inspiration that makes scientists scientists. As teachers we must be willing to respond humanly to this wonder. Any response, however, that denies the past is a sham and advances the distorted images of science. Science is more than facts—it is also the pathway to facts. In most cases the path has been uphill. Along the way men have argued passionately, shouted triumphantly, and rode home on subways contentedly. Philosophic systems have been modified, religious beliefs affected, and world politics influenced. And throughout it all is the hand of man.

References

1. M. Mead, R. Metraux, Science **126**, 384 (1957).
2. D. Beardslee, D. O'Dowd, Science **133**, 997 (1961).
3. R. Feynman, in *Frontiers of Science—A Survey*, E. Hutchings, Jr, ed., Basic Books, New York, 1958, page 260.
4. J. Platt, *The Excitement of Science*, Houghton Mifflin, Boston, 1962, page 4.
5. K. Popper, *The Logic of Scientific Discovery*, Basic Books, New York, 1959, page 59.
6. P. Kusch, Bull. At. Scientists, October 1968, page 41.
7. L. Eiseley, *The Mind as Nature*, Harper and Row, New York (1962).
8. I. I. Rabi, in *The Scientific Endeavor*, Rockefeller Institute Press, page 306.
9. *Dialogues of Alfred North Whitehead* as recorded by Lucien Price, Little, Brown, Boston, 1954, page 345.
10. A. Landé, *From Dualism to Unity in Quantum Physics*, Cambridge U. P., 1960, page *vii*.
11. E. Bright Wilson Jr, *Tetrahedron* **17**, 191 (1962).
12. E. Rabinowitch, Bull. At. Scientists, October 1968, page 23. □