Is physics human?

Yes, it is, even though to some people it seems contrived, mathematical, abstract and distant; to overcome these negative impressions it is the physics teacher's task to emphasize the human side.

Victor F. Weisskopf

There are many people who assert that physics is not "human"; in the view of these people, the methods of physical research and the results obtained from it do not touch on those values, emotions and sentiments we associate with the word "human." Physics, they claim, has little to do with human relations, with those experiences that are of importance in the world of feelings and emotions, with our being members of a family and a human society or with any contacts of one human being with another.

There is one side of this alleged "inhumanity" of physics that I would like to exclude from this discussion: In this article I will not discuss the inhumanities caused by the application of physics to technology; nor will I discuss the use of physics discoveries for the design of new weapons of destruction or the detrimental effects of modern science-based technology upon the natural and social environment in which we live.

The charges against physics

Why is physics as a science considered "inhuman" by so many people, including some of our own students? Let me divide the reasons into four groups, which roughly can be described by the following assertions:

1. Physics is far removed from direct human experience.
2. Physics is quantitative and based on mathematics.
3. The basic concepts of physics are too abstract.
4. Much of modern physics deals with matter under conditions far removed from the human environment.

Let us start with the first point, which expresses the feeling that the approach to the phenomena in physics does not correspond to our direct experience. What the physicist considers essential in a natural phenomenon is quite different from what the layman may consider so. The physicist tries to isolate certain processes from the flow of events because he is convinced that they contain the essential information he seeks. Those processes do not appear to be "natural" to the layman. I have often observed the astonishment of a layman entering a physics laboratory, where he sees the usual complicated mass of wires, electronics, and other instrumentation. "With these tricks you intend to get at the essentials of Nature? It looks as if you torture it and destroy what you are seeking to find out!"

A hundred and fifty years ago, Goethe argued against Isaac Newton along these lines when he ridiculed Newton's method of decomposing white sunlight into colors. He wondered how one could obtain relevant information about bright sunlight by squeezing the light through a narrow slit in a dark room. The poetic expression of Goethe's argument is reproduced in the Box on the next page. The feeling exists that the methods of physics somehow exclude some essential part of Nature from being recognized.

The second point is based upon the undeniable fact that a large part of the population is turned off by mathematics, even in its simplest form. I will not argue here whether this could be remedied by a better way of teaching mathematics or whether it is altogether unavoidable. In any case, the mathematical formulation of natural events is considered by many as an inhuman way of talking about human experiences. It is true that the lack of appreciation for simple mathematics is a formidable obstacle to an appropriate understanding of natural events. I recognized this aspect in its full force one day when I tried to transmit to a person not versed in mathematics the intense joy and satisfaction we experience when we go through Newton's argument that the free fall on Earth of a pebble leads directly to the monthly revolution of the Moon around the Earth, solely on the basis of the natural assumption that the force decreases with the square of the distance. The person was a most sensitive human being, deeply interested in Nature and thought, but I was not able to reach my aim because those simple mathematical steps appeared to him as an endlessly drawn out sequence of small logical steps in which all excitement is quenched. Let the poets speak once more—this time it is Walt Whitman:

When I heard the learn'd astronomer;
When the proofs, the figures, were ranged in columns before me;
When I was shown the charts and the diagrams, to add, divide, and measure them,
When I, sitting, heard the astronomer, where he lectured with much applause in the lecture-room,
How soon, unaccountable, I became tired and sick,
Till rising and gliding out, I wander'd off by myself,
In the mystical night-air, and from time to time,
Look'd up in perfect silence at the stars.

A bridge between nations

Recognition and enjoyment of even the most elementary insight in physics requires a knowledge of, and a facility with, a new language, the language of mathematics. You can not enjoy poetry in a language unknown to you. In this sense

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every introductory physics course is like teaching a foreign language. Here physics teachers are at a tremendous disadvantage compared to teachers in the humanities. Compare a freshman course in physics with a freshman course in literature. The literature teacher is able to talk to the student on equal terms directly about the emotions and thoughts engendered by reading a particular work of art. The physics teacher can not; he must teach the language first. In physics it is a one-sided affair: the teacher teaches, the student learns, whereas in literature, student and teacher are on the same level of approach—if not of sophistication. Elementary language courses always lack excitement until the student masters the new language to some extent and can begin to talk in it.

There is, however, a positive side to the fact that physics requires a new language. This language is international and independent of cultural, social and political background. Once it is learned, it not only serves us in understanding Nature but it also serves as a bridge between nations and as a step towards a more united mankind.

We now come to the third point. The concepts that are most fundamental for a true insight into the workings of Nature are rather abstract and far removed from our direct intuitive understanding. There are many examples for this; let me mention the concepts of entropy, electromagnetic field, relativity and, last but not least, the whole conceptual framework of quantum mechanics, upon which our modern physical understanding of the properties of matter are based. The difficulties encountered here are not necessarily mathematical; they are conceptual. Again much training and experience is needed before we can grasp the significance of these concepts. In contrast to concepts used in the humanities, there is little or no intuitive preparation or preformation of these concepts in the culture of today. This is why these concepts appear "inhuman" to the uninitiated. Once assimilated, they will be recognized as an expression of the most significant relations between Man and Nature.

The fourth point concerns recent physics. Many of the processes that are in the center of interest today seem to be far removed from ordinary human environment. I refer to nuclear or subnuclear phenomena, astrophysics, low-temperature physics, plasma physics and so on. The interest of today's researchers is centered upon matter under very unusual conditions, which are realized in Nature only at far away places of the universe. In nuclear physics we study phenomena with interatomic energy exchanges of millions of electron volts; this happens in Nature only in the centers of stars or during star explosions. In particle physics the energy exchanges are at least a thousand times higher; apart from rare cosmic-ray events, such exchanges take place only in neutron stars or perhaps during the first few instants of the big bang. Plasma physics deals with phenomena at unusual pressures and temperatures and so does low-temperature physics. Naturally, astrophysics looks into phenomena far away from us. Why should we be interested in the behavior of matter under such "inhuman" conditions? There is, of course, an intense technological interest in some of the examples mentioned—but we have excluded that point of view from our considerations at the outset of this article.

These four points should serve as examples and illustrations of why physics appears "inhuman" to many people. My

What Goethe thought of Newton's experiment

Freunde, flieht die dunkle Kammer,
Wo man euch das Licht verzwickt
Und mit kümmerlichstem Jammer
Sich verschrobnen Bildern bückt.
Abergläubische Verehrer
Gab's die Jahre her genug,
In den Köpfen eurer Lehrer
Laβt Gespenst und Wahn und Trug.

Wenn der Blick an heitern Tagen
Sich zur Himmelsbläue lenkt,
Beim Sirok der Sonnenwagen
Purpurrot sich niedersenkt:
Da gebt der Natur die Ehre,
Froh, an Aug' und Herz gesund,
Und erkennt der Farbenlehre
Allgemeinen ewigen Grund.
—Goethe, *Zahme Xenien*

Friends, escape the dark enclosure,
where they tear the light apart
and in wretched bleak exposure
twist, and cripple Nature's heart.
Superstitions and confusions
are with us since ancient times—
leave the specters and delusions
in the heads of narrow minds.

When you turn your eyes to heaven
skyward to the azure flow,
when at dusk the Sun is driven
down in crimson fireglow
There in Nature's deepest kernel
healthy, glad of heart and sight
you perceive the great eternal
essence of chromatic light.
—Translation by Douglas Worth and the author.

BAUSCH & LOMB

answer to the question posed in the title of this talk is simply: Yes, physics is indeed human; it can and should be made to appear so in our teaching and writing. This is the first and foremost task of the physics teacher. Let us now go through these four points again with some remarks as to how we may emphasize the human angle of our science.

The case for the defense

Back to Point 1. Since the beginning of culture Man has been curious about the world in which he lives. Early theories were developed in a mythological framework. The explanations were directed at the totality of Nature; they attempted to account for everything from beginning to end. Five hundred years ago, however, human curiosity took a different turn: Instead of reaching for the whole truth, people began to examine isolated and clearly separable phenomena. General questions were shunned in favor of limited ones.

This restraint has paid off. The renunciation of immediate contact with absolute truth, the endless detour through the diversity of experience, has allowed the methods of science to become more penetrating and their insights to become more fundamental. The study of moving bodies has led to celestial mechanics and the universality of the gravitational law. The study of friction and of gases has developed into a comprehensive theory of heat. The study of the twitches of frog muscles has led to Maxwell's equations and to the recognition of the electric nature of matter. By means of the detailed questioning of Nature a framework has been created for a far deeper understanding of the natural world than we have ever had before. Our earlier discussion of Point One refers to those apparently endless detours in the detailed questioning of Nature; these only appear to the outsider to be too far removed from the direct experience of the phenomena under investigation.

Therefore one way of overcoming this difficulty is to take the historical approach in teaching physics. It may help to clarify the necessity and the importance of studying phenomena especially contrived to maintain "sterile" conditions of strict separation from other influences. It would show that such a seemingly "unnatural" approach to Nature has indeed revealed the essential traits of Nature and established a deeper relation between Man and his environment. It is the great miracle of science that it was such a successful enterprise. As Albert Einstein said: "The most incomprehensible fact of Nature is the fact that Nature is comprehensible."

Another way to meet this problem is an early involvement of the student in experimental research. He or she will see how important all these wires, amplifiers and gadgets are for the penetration into the essential processes of Nature and—if the student has not made a very bad choice of a team—will witness the deeply human enthusiasm with which most physicists try to get at these processes. The student will participate in the immense joy of finding something new, even if it is only a tiny bit of an essential insight.

The most incomprehensible fact of Nature is the fact that Nature is comprehensible. —*Einstein*

ATELIER JACOBI; NIELS BOHR LIBRARY

Einstein at Caputh, circa 1930.

I have little advice on how to remedy the situation described in Point Two. It is indeed impossible to transmit most physical insights without the aid of some mathematics. Nevertheless some ideas can be transmitted with a minimum of quantitative thinking. When teaching an introductory physics course, the teacher should make use of qualitative thinking whenever possible. He should be aware that he teaches a language and he should use that language as early as possible for some "poetry"—for the revelation of basic and unexpected connections in Nature. The student should see and feel that quantitative relations do indeed reveal essential aspects of Nature.

Pattern into structure

I have more to say about Point 3, which deals with the abstract nature of some of the fundamental concepts, but I will restrict myself to some remarks about quantum mechanics. Let me stress the fact that quantum mechanics has introduced the elements of form, shape and symmetry into physics. Nature—from crystals to flowers—is full of ever recurring characteristic shapes and symmetries. There must be a fundamental reason for the typical properties of materials and forms that we observe in the flow of natural events. This reason is found in quantum mechanics: The wave nature of electrons forces them into typical patterns, the shapes of standing waves in the spherically symmetric Coulomb field. These shapes are the fundamental patterns of Nature, which are the basis of all the shapes we observe—the German language has a better expression: *die Urformen der Natur* (roughly translated, the primitive forms of Nature). This "morphic" character of quantum mechanics was pointed out to me by Laszlo Tisza of M.I.T., who emphasized the basic importance of this trait.

These forms not only exhibit the typical shapes of atoms but also a stability against changes and an ability to regenerate after having been perturbed by influences from their surroundings. Nature combines these patterns, puzzle-like, into molecular structures exhibiting the ever recurring variety of substances that we find in our environment—from minerals to the macromolecules that are the basis of life.

The significance of quantum mechanics becomes clearer when we realize that only the wave–particle duality can give us those stable and regenerating patterns that form the basis of Nature. Classical physics with its atoms as planetary systems is incapable of reproducing the most obvious facets of Nature. Indeed quantum mechanics is a simpler explanation of the nuclear atom than is the classical theory. The quantization of electron orbits and the simple superposition laws make quantum mechanics a much easier theory for treating the motion of electrons under the influence of nuclei than classical mechanics. Unfortunately the difficult classical problem is not merely an academic task; it occurs in plasma physics, when high temperatures force the electrons into highly excited orbits with dynamics the same as those of the classical motion. Plasma physics indeed poses almost intractable problems involving the

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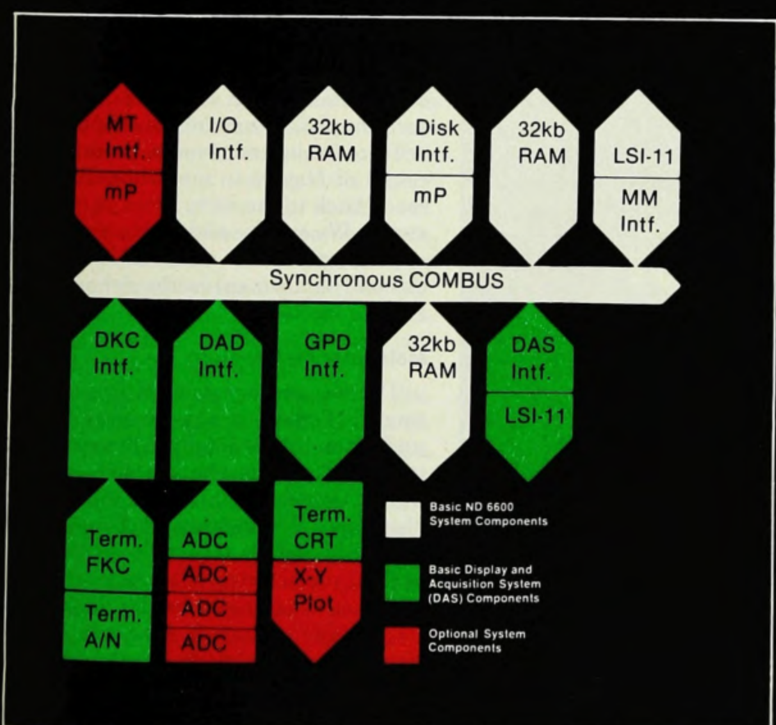

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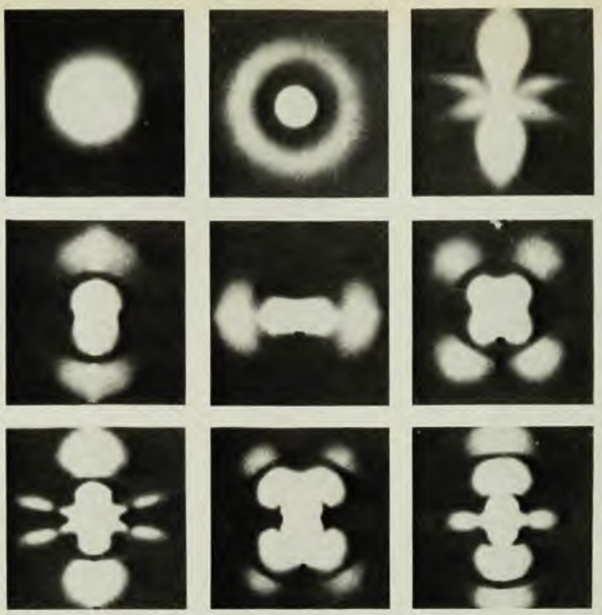
The wave nature of electrons forces them into typical patterns, the shapes of standing waves in the spherically symmetric Coulomb field.



interactions of many charged particles.

The physics of the far away

We now come to Point 4, which stresses the apparent remoteness from human interest of some of the topics in recent physics, such as particle physics or astrophysics. For astrophysics, strangely enough, no strong defense is needed against this accusation. Somehow studies of the universe and its strange objects have always attracted the minds of persons outside the astronomical disciplines. Today the objectives of these fields have become even stranger—I am thinking of neutron stars, quasars and black holes—and the history of the universe has become a subject of scientific research. Questions of the beginning and the end of everything are coming within the reach of science, and there even appear to be observations of some of the reverberations of the big bang with which everything began: the 3 K radiation filling the universe. These questions have a strong human appeal, although they are dealing with objects that are enormously far away in time and space from the human scene. Perhaps this is so because these questions are the same ones that are dealt with in the old mythological and religious traditions; there is an innate urge to know about the ultimate whence and whither.

The situation is different in nuclear and particle physics. Here we also deal with phenomena far removed from our terrestrial environment. Tremendous efforts are spent in building accelerators that serve to produce the processes under investigation. The seeming lack of human appeal of these studies comes from the question of why one should be interested in processes that need such "inhuman" efforts to realize. Again I leave out the important problems and promises that nuclear technology has posed.

I think that there are direct answers to this question that show the fundamental relevance and importance of studying nuclear and subnuclear processes. Unfortunately the scientists engaged in this work have not exerted enough efforts to communicate with the public and have not shown enough eloquence and persuasion to convince students and outsiders of the true significance of their work. It seems to be more difficult to do so than for astronomy, probably because the innate urge to know about the innermost structure of matter is not as strong as the urge to know about the cosmos at large.

There are many ways to argue against Point 4; I will mention only a few. First of all, it is probably correct to say that much more matter in the universe is found under conditions where nuclear processes are active than under conditions where molecular physics of the terrestrial kind (including life) is of relevance. Indeed, nuclear processes are the source of stellar energy and therefore they are the precondition of human existence.

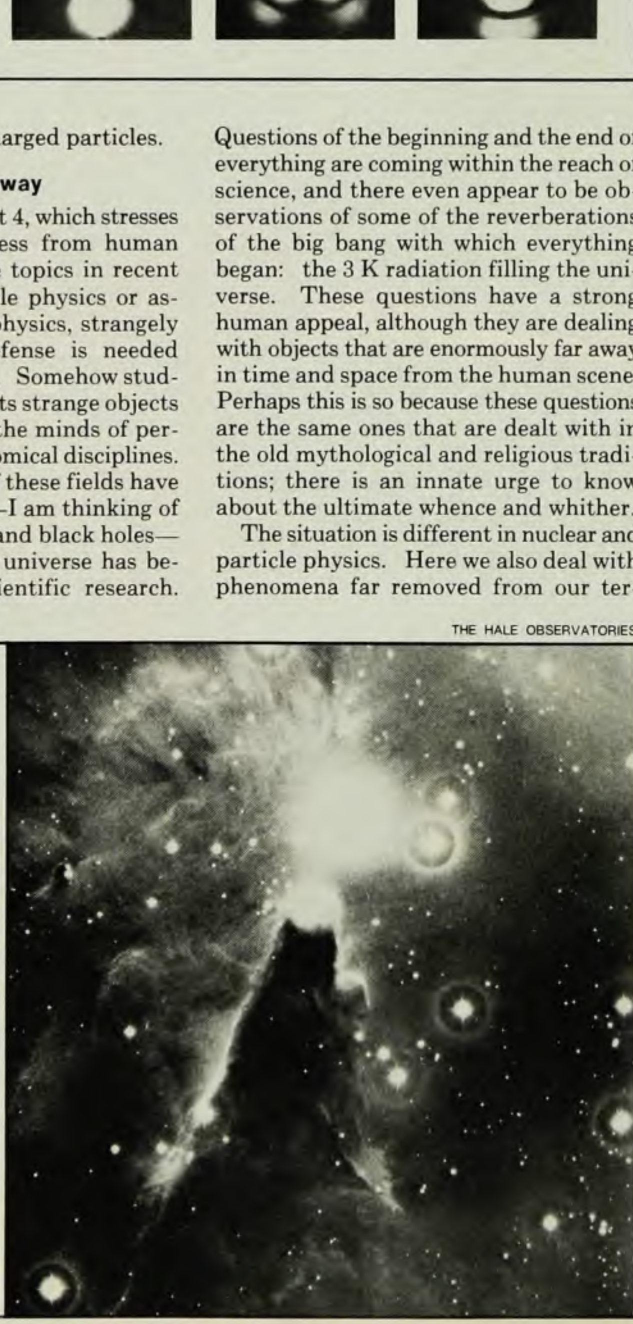
In modern particle physics the situation may be different, because the necessary energy exchanges that produce the phenomena studied in that field are so large that even the interiors of stars are not hot enough to bring them forth. Perhaps only the particles within neutron stars get near to such energy levels; only during the first moments of the big bang were conditions possibly such that the processes produced with our big accelerators occurred abundantly. However, there is a certain spirit of romance and human adventure in the endeavor to produce processes of Nature in our laboratory that reach back to the early times of our universe. We explore and excite new worlds of phenomena that, under ordinary conditions, lie dormant in the deepest confines of matter.

Molecular architecture

There is another point of great importance: Today we have a basis for the understanding of chemical processes. It is the quantum mechanics of the electric interaction between atomic nuclei and electrons. We understand the principle, if not the details, of why electrons and atomic nuclei form molecules of all sorts, including the macromolecules that are the basis of life. There is one essential feature that is basic for the structure of molecules: the large mass difference between nuclei and electrons. Nuclei are between a thousand and ten thousand

THE HALE OBSERVATORIES

The scientific insights of our age shed such glaring light on certain aspects of experience that they leave the rest in even greater darkness. —*Fierz*



times heavier than electrons. This ratio is responsible for the "architecture" of molecules, for structural properties such as the helical form of DNA. It makes it possible for nuclei to have well defined positions in the molecule, whereas the electrons with their low mass act as the distributed glue to the structure. Without this large mass ratio there would be no molecular architecture.

Why are nuclei so heavy? They consist of protons and neutrons that are about 2000 times heavier than the electron, but the reasons for this are essentially unknown to us. We know that this difference in mass comes from the fact that the nucleons—protons and neutrons—are the source of the nuclear force, but we do not know the origin of this force. The only way to get at the explanation of this mass difference is study of the internal structure and dynamics of the nucleon, and this is the object of particle physics.

Another fundamental question bearing on the structure of matter is the nature of electric charge. Why does it occur only in multiples of e, the electronic charge? The reason for that value and no other is completely unknown. In particular the mysterious ratio of e^2 to the product hc of Planck's constant and the light velocity is of fundamental significance for the structure of matter. If that ratio were of the order unity the world as we know it could not exist! The study of this problem is also part of modern particle physics. By trying to solve these fundamental problems of human existence, physicists have been forced to penetrate deeper and deeper into the innermost regions of matter. A whole new world of mesons, hyperons and quarks was opened up that demonstrates how Nature is so much richer and multifaceted than the human mind could ever have conceived.

The urge to find out

Let me come back to the question: "Is physics human?" I definitely would answer this question in the positive. It is human because it is nothing but a highly developed form of the urge to find out where we are in the environment into which we were born. This urge is common to all people regardless of their culture or their nationality; this is why it is an activity in which all human beings can and do participate equally.

This supernational character of the scientific community is an important element of the human side of science. Scientists, in particular physicists, often have contributed to the better understanding among nations even in non-scientific issues. The Pugwash movement is an example of the ability of scientists to approach sensitive questions with greater ease and lesser danger of misunderstandings because of the supernational character of science. CERN, the high-energy research center in Geneva, where the European nations have been able to achieve a degree of collaboration that was impossible to attain in other fields, is perhaps another example of this.

In this article I have endeavored to show that physics is indeed a very human activity in that it expresses the relation between Nature and Man, a relation that becomes ever more intimate and involved because of the growing understanding of Nature by human beings. This growth has been rather fast during this century. It has led to an ever more rapid growth of technical applications, with all the effects, both beneficial and detrimental, these have had on our way of life.

This rapid growth has had other effects too, of a more philosophic character. The Swiss physicist–philosopher Marcus Fierz once said that "the scientific insights of our age shed such glaring light on certain aspects of experience that they leave the rest in even greater darkness." I believe that some of the aversions to physics and to science in general are connected with the rapid growth of science. It has led to the generally accepted claim that, in principle, science can and will find an explanation of every human experience.

I am not so sure that this claim is justified—but even if it were so, the scientific explanation of a human experience does not necessarily touch all aspects of this experience. Indeed, in some cases it may not include the most relevant aspects. A simple example is the phenomenon of an artistic experience, say the enjoyment of a Beethoven sonata. It can be interpreted acoustically or neurophysiologically or even psychologically. However, there is something in that experience that is not covered by these scientific descriptions; yet that something is probably the most relevant part of it.

There are many other examples in the relations between human beings, and also in the relations between Man and Nature, in which the scientific interpretation may not cover all aspects of the human experience. This is particularly so for those aspects that are connected with concepts such as love, dignity and beauty. The beauty of a scientific insight is an example of nonscientific aspects playing an important role in science itself. Perhaps the recognition of the intrinsic value of physics could be enhanced if there were a greater awareness of the fact that science is only one way—albeit a very important one—of establishing a relation between mankind and its natural and social environment.

* * *

This article is based on the author's response as recipient of the Oersted Medal of the American Association of Physics Teachers at the 1976 joint annual meeting of the AAPT and The American Physical Society and on a similar paper presented by the author at the International Conference on Physics Education (Edinburgh, 31 July–6 August 1975), which appeared in Physics Education *11, 75 (1976). The Whitman poem on page 23 is from* Leaves of Grass, *Doubleday.* □