Sensuous-Intellectual Complementarity in Science

Countercultural epistemology has something of value to contribute to the science of complex systems.

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We live in a technological culture, and that culture is in trouble. Recent essays (*1–3*), that have explored the relationship between modern science and the history and psychology of technological man, have generally concluded that the scientist's quantifying, value-free orientation has left him helpless to avoid (and often a willing partner in) the use of science for exploitative and destructive ends.

The past few years have seen the rapid growth of a counter-technological culture in which science, as we know it, plays no role in the contemplation of nature. The counterculture, because it is still in the process of growth and formulation and because of its very nature, is no single philosophical system. For our purposes, the salient feature of the counterculture is its epistemology of direct sensuous experience (*4*), subjectivity, and respect for intuition—especially intuitive knowledge based on a "naive" openness to nature and to other people. Both on its own merits and as a reaction to the abuses of technology, the movement has attracted increasing numbers of intelligent and creative students and professional people. I believe that science as a creative endeavor cannot survive the loss of these people; nor, without them, can science contribute to the solution of the staggering social and ecological problems that we face.

More fundamentally, much of the criticism directed at the current scientific model of nature is quite valid. If society is to begin to enjoy the promise of the "scientific revolution," or even to survive in a tolerable form, science must change. In its own terms, the logical-experimental structure of science that has evolved since Galileo's lifetime is magnificent. It has, in Lewis and Randall's phrase (*5*), its cathedrals. To demolish these, to reject what has been achieved, would be barbaric and pointless, since the very amorality of science makes it not wrong, but incomplete. The claims of science as such (as opposed to, say, "defense" research), as well as the claims of its critics, while contradictory, are not incompatible.

Niels Bohr's concept of complementarity arose when apparently conflicting results in elementary particle physics forced an expansion of the frame of reference of classical physics (*6*). Bohr himself came increasingly to believe that complementarity was a concept that could be applied to far more than just the purely physical systems that had led him to its formulation (*7*, pp. 3–22). It is conceivable, then, that the notion of complementarity offers a method of including both sensuous and intellectual knowledge of nature in a common frame of reference. The result, far more than a mere compromise or amalgamation of the two viewpoints, could be a richer science, in which esthetic and quantitative valuations, each retaining its own integrity, would contribute equally to the description of nature that science long ago took for its province. Further, it may produce a scientific ethic that is less destructive toward nature.

Complementarity in Modern Physics

Phenomena on the atomic level present the investigator with a wealth of seemingly contradictory observations. Light undergoes diffraction, which can only be explained by adopting the classical wave model. Yet, in the photoelectric effect and in photon-scattering experiments, the predictions of the wave model are not realized, and the actual observations can only be rationalized by postulating quanta of light that carry momentum and have a relatively definite location (subject to the restrictions of the Heisenberg uncertainty principle). Again, negative electricity is first found to be quantized in electrolysis and the oil-drop experiment, and each unit of negative electricity behaves in a cathode-ray tube like a little lump, with a mass of 9×10^{-28} gram, and a charge of 4.8×10^{-10} electrostatic unit. Yet, direct a stream of these "particles" onto a crystal, and diffraction phenomena take place; to explain these phenomena requires that the "electrons" be treated as a train of waves. Attempts to measure the position and momentum of a particle, or the energy and duration of a state of a dynamic system, may be perfectly successful in separate experiments, but never in the same experiment on the same system.

All of these familiar results of quantum physics are given a quantitative expression in the Heisenberg uncertainty principle, and a general philosophical basis in Bohr's principle of complementarity. Viewing these phenomena from the standpoint of deterministic descriptions of events in space and time (the goal of classical physics), Bohr says: "Within the scope of classical physics, all characteristic properties of a given object can in principle be ascertained by a single experimental arrangement, though in practice various arrangements are often convenient. . . . In quantum physics, however, evidence about atomic objects obtained by different experimental arrangements exhibits a novel kind of complementary relationship. . . . Far from restricting our efforts to put questions to nature in the form of experiments, the notion of *complementarity* simply characterizes the answers we can receive by such inquiry, whenever the interaction between the measuring instruments and the objects forms an integral part of the phenomena" (*8*).

And again, "Indeed the ascertaining of the presence of an atomic particle in a limited space-time domain demands an experimental arrangement involving a transfer of momentum and energy to bodies such as fixed scales and synchronized clocks, which cannot be included in the description of their

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functioning, if these bodies are to fulfill the role of defining the reference frame. Conversely, any strict application of the laws of conservation of momentum and energy [that is, any causality] implies, in principle, a renunciation of detailed space-time coordination of the particles" (*8*).

After complementarity in physics had been accepted, it was realized that observations which give conflicting (complementary) views of phenomena cannot, when taken by themselves, be accepted as complete *nor, therefore, as totally correct* descriptions of nature. Electrons behave in ways that can be accounted for by thinking of them as particles; but they are *not* particles, since they also (under different conditions of observation) behave in ways that can be accounted for by thinking of them as waves. Only the complementary description is complete and, to the best of our knowledge, correct. However, to say this is not to impugn the accuracy of the different experimental measurements that give, respectively, the one-sided wave or particle results.

Bohr made it very clear that, in the context of quantum physics, the idea of complementarity had nothing to do with any renunciation of rational objectivity in science. Yet the very idea of an objective description of phenomena (for example, in unambiguously reporting the results of an experiment) requires that macroscopic (that is, classical) equipment and observations be described in ordinary language, no matter how much that language could be refined and specialized for technical usage. The duality of light's behavior arises not from the light "itself" (if such an idea even has any meaning), but from the observation of light as it interacts with experimental equipment and in the description of such observations in language that only contains the classical terms "wave" and "particle" as models for the phenomenon.

Although it was the phenomena of quantum physics that forced Bohr to the idea of complementarity as a mode of knowledge, he quickly realized that other apparent contradictions in the description of nature also admitted of a similar resolution. In a series of essays, he considered its application to biology and psychology (*8*) and, finally, to the whole range of human intellectual experience (*7*, pp. 67–82). Since the extension to wider problems of an idea that is valid in a clearly limited context is dangerous to the integrity of that idea, the present attempt at even further extension requires a list, as complete as possible, of the characteristics both of the idea of complementarity, and of the situations to which it may be fruitfully applied. It will then remain to discover to what extent the conflict between the analytical and intuitive understandings of nature satisfies those criteria. I intend to use only the physical application of complementarity as a model, since it seems the least ambiguous and is generally accepted as a necessary interpretation of phenomena by workers in the field.

On this basis, then, the following characteristics defining complementary realities may be listed:

1) A single phenomenon (for example, "light" or "matter") manifests itself to an observer in conflicting modes (for example, as "waves" or "particles").

2) The description or model that fits the phenomenon depends on the mode of observation. (In this way, the idea of objectivity is somewhat broadened, but not eliminated.)

3) Each description is "rational"; that is, language (including mathematics if necessary) is used according to the same consistent logic in either description, with no appeal to revealed truth or mystical insight.

4) Neither model can be subsumed into the other. Thus, for example, classical and statistical thermodynamics do not constitute complementary formulations, even though they can be developed from apparently independent axiomatic bases.

5) Because they refer to a (presumably) single reality, complementary descriptions are not independent of each other. For example, the differential equation of wave motion used in the description of an electron in an atom must be "normalized"; that is, its integral over all space must correspond to the quantity of mass and electrical charge carried by one electron (measurable only in experiments in which particle behavior is manifested).

6) Complementarity is not mere contradiction. The alternate modes of description never lead to incompatible predictions for a given experiment, since they arise from different kinds of experience. Thus, Newtonian and relativistic mechanics are not complementarities, since it can be shown experimentally that the former leads to incorrect predictions of phenomena that are correctly predicted by the latter.

7) It follows from number 6 that neither complementary model of a given phenomenon is complete; a full account of the phenomenon is achieved only by enlarging the frame of reference to include both models as alternative truths, however irreconcilable their abstract contradictions may seem.

Quantitative Science and the Sensuous Alternative

The importance of quantitative modeling in the creation of the scientific world view is an old story, and there is no need to belabor it here. Critics and apologists of science alike have recognized that the cyclic coupling of experimental observation with mathematical theorizing has been the driving force behind the huge advances achieved since the time of Descartes in understanding the complex of phenomena that we call nature. Where critics and apologists have parted, however, is on the moral consequences of such an approach to nature. Some, like C. P. Snow (*9*) and J. Bronowski (*10*), find in the scientist's rigorous adherence to verifiability, and in his humility in the face of evidence contradictory to his theories, the best hope of salvation that mankind has. To others (*2*, p. 205), the alleged objective consciousness of the scientist is not only a myth, but a vicious one, behind which men may perpetrate monstrous crimes against nature without acknowledging personal involvement and, therefore, guilt. Most recently, Lewis Mumford (*3*) has found in the mechanical world view the fatal metaphor for a society of machine-like repression of human feelings and human freedom. It is not my purpose to evaluate Mumford's critique of science [which is sometimes too condemnatory even for the generally antitechnological *New York Review of Books* (*11*)]. It seems to me, however, that some undeniably dangerous attitudes do exist in science's present stance toward nature; and, to the extent that these attitudes exist, they represent dangers to the integrity of human freedom and of the terrestrial environment.

In his everyday experience, man finds the world chaotic and, in the perhaps revealing word of the scientific theorist, "messy." Complex brown and black mixtures prevail over pure substances. It is no wonder, then, that mankind, in reaction to this chaos, is inclined to bring the phenomena indoors to calm, well-lighted laboratories in which they can be studied one at a time, or in well-defined combinations. Nor is it any wonder that he often chooses to understand nature in terms of mental models (which include scientific theories and "laws" as well as pictorial or tactile models) that are understandable just because they are the creation of his own mind. These mental models serve as maps or blueprints of reality. Like maps and blueprints (and like shadows), they simplify complex systems by projecting them onto a simpler space that has a smaller number of dimensions than are required for a complete description of the original system. A complex part of nature (such as a coral reef, a cell, or a city) is, metaphorically, many-dimensional. It is brought under scientific scrutiny by projecting it onto a simpler, underdimensioned space, within which it can be grasped and quantified.

Then, depending on its appearance within that space, generalizations are drawn according to the logical and mathematical rules appropriate to the quantification space. Physical implications of the mathematical model are subjected to quantitative test under controlled conditions. To the extent that experiment confirms theory and suggests new theoretical steps, science progresses.

The pure intellectual excitement of science, its success in illuminating some of the darkness that threatened to engulf us with the fall of religious world views, and the social benefits of its technological consequences are beyond serious question. There are those who are chafing to get on with the extension of mankind's intellectual hegemony to the understanding and complete control of our natural environment, our societies, our heredity, and our fellow man. Yet the potential and actual evils that have already come from the "ethically neutral" pursuit of knowledge for its own sake, and the alienation of science and scientists from the rest of the culture, are also beyond question. To take credit for the successes of science and the blessings of technology, but to blame the abuses on the incompetence or venality, or both, of planners, politicians, and businessmen, seems fatuous in the extreme. Nor, knowing what we do now of the momentous social consequences of the "purest" science, can we seek forgiveness for the next social or ecological disaster. Our understanding of really complex systems (organisms, societies, ecosystems, the mind) is rudimentary, and our ways of investigating such systems and communicating about them, primitive. The danger of a scientific-technological disaster arises when practitioners of the quantifying art forget about the philosophical foundations of their enterprise. It is easy to ignore the too-messy world outside the laboratory door: to mistake domains and functions in quantification space for nature, and the manipulation of these for the only method of understanding nature. (As a physicist once remarked to me in the course of a seminar on group theory, "The matrices are all there is.")

I realize that the connection I have just made between scientific practice and ethics is a tenuous and controversial one, though Roszak and Mumford make it with great force. In fact, Alfred North Whitehead made just these points over 40 years ago in his widely admired and little heeded series of lectures, *Science and the Modern World* (*12*). However, by relying lopsidedly on abstract quantification as a method of knowing, scientists have been looking at the world with one eye closed. There is other knowledge besides quantitative knowledge, and there are other ways of knowing besides reading the position of a pointer on a scale. The human mind and body process information with staggering sophistication and sensitivity by the direct sensuous experience of their surroundings. We have, in fact, in our very selves, "instruments" that are capable of confronting and understanding the blooming, buzzing, messy world outside the laboratory. If that were not so, *Homo sapiens* would never have survived the competitive pressure from predators who are also so equipped. There are three tenets of countercultural thought that, it seems to me, hold great promise for the enrichment of scientific practice and, perhaps, for the improvement of scientific morality.

1) The most reliable and effective knowing follows from direct and open confrontation with phenomena, no matter how complicated they are. Nature can be trusted to behave reliably without suppression of the manifold details of a natural environment, and nature's ways are open to direct, intuitive, sensuous knowledge.

2) It follows from the first point that, to know nature well, the human body is to be trusted, cherished, and made sensitive to its natural and human environment. Since the self and the environment are inextricable (contrary to the philosophical stance of classical science), one can understand his surroundings by being sensitive to his own reactions to them.

3) Because knowledge of nature is, in this way, equally open to all, the "expert" is highly suspect. His expertise is likely to be confined to abstractions, and there is a danger that he will project sensitive and complex problems onto some underdimensioned space where he feels less involved and more in control of phenomena. (This threatening aspect is generally confined to the psychological and social sciences, but it can also be seen in the attitude of the ecology movement toward the Army Corps of Engineers.)

In sum, it seems to me that there is much of value in the mind-set that includes these ideas. It is certainly not confined to hippies and "eco-freaks." Thoughtful and respectable writers on educational theory (*13*) hold much the same view of learning and have much the same criticism of conventional knowledge, which is based on quantification. Furthermore, for very different reasons, industrial scientists have been telling academic scientists this for years. Industrial scientists have attacked what they see as a ludicrous overemphasis on abstract theory in science education. In fact, it may be just the academic scientist's self-imposed isolation from the complexities of the "real" world that has made him so helpless to curb the ecological abuses of his profit-motivated colleagues.

A Complete Natural Science

I now consider whether abstract-quantitative and direct sensuous information meet the requirements of a complementary description of nature.

1) The language, the epistemology, and the models of the two approaches all present us with conflicting pictures of nature; yet the phenomena are consistent and repeatable in each mode.

2) Which description of nature one gives depends entirely on one's method of knowing. For example, one can predict rain by reading the barometer or by going outdoors and sniffing the air, with about equal reliability. The explanations of the prediction, though, will differ, depending on the manner in which the experiment was performed on the atmosphere.

3) Though it may be difficult to

convince partisans of either viewpoint, both approaches are "rational." That is, both use a consistent logic, based clearly on the observation of phenomena, in such a way as to ensure that another observer in the same situation would come to the same conclusion. (Before conventional scientists rush in with cries of "subjectivity" in criticism of the sensuous approach, they might stop to consider whether or not a person selected at random off the street could be asked to repeat their highly sophisticated observations. "With the proper training he could," they reply; and the reply of the sensuous observer of nature would be exactly the same for *his* method.)

4) It goes without saying that neither approach to nature can be subsumed into the other. A number is not an experience, nor is an equation the same thing as intuition. These things are projections of nature into separate (disjunct) mental spaces.

5) Sensuous information is not independent of quantitative knowledge, since they both have their referent in the same system of nature. Of course, abuses of both methods are possible: drug- or wish-induced distortion of the senses, and politically or economically motivated suppression of contrary data for the quantifier. [The controversies in Russia over genetics and those in the United States over the carcinogenicity of smoking have been fought entirely on traditional, theory-experiment grounds. They recall the happiness of Watson and Crick when a colleague guessed the *wrong* structure for DNA (*14*).] Yet in the long run, such distortions are corrected or at least forgotten, since both the sensuous and experimental investigator share humility in the face of nature.

6) By the same reasoning, both sensuous and quantitative descriptions of nature may be true; they lead, by the process of continuous self-correction, to reliable models of nature. The woodsman or farmer knows when to expect rain or frost, or where to find a given animal, without quite knowing *how* he knows these things. Reasonably accurate descriptions of weather patterns and animal behavior may also emerge from the tabulation and correlation of quantitative data.

7) Finally, neither sensuous nor quantitative knowledge of nature is complete. In fact, it should be clear from the examples I have chosen that each is really an undernourished view of nature, because each lacks the information available through the other mode. Indeed, it is difficult to think of single problems that have been attacked by both modes of knowing, so different are the mind-sets of the two classes of investigators.

The theoretical-experimental mode has built its grand structure by confining the phenomena investigated to the kind that can be brought into a laboratory. Worse, because such laboratories and their operation are very expensive, the phenomena investigated have largely been confined to those in which a source of wealth has a vested interest—however broadly that interest has been expressed, and however apparent has been the freedom of the investigator to follow knowledge for its own sake.

On the other hand, the sensuous investigation of nature has generally been confined to "naturalists." Their undoubted and often sublime understanding of nature, and the integrity they have preserved by being poorly funded, have been undercut by their concomitant (in fact, complementary) weakness in rigorous quantitative formulation of what they know. Competition for funds and recognition has made naturalists and scientists rivals, mutually indulgent at best, contemptuous at worst, rather than colleagues in the process of learning about nature. The two groups are, in fact, comparable to two groups of physicists, one of which insists on regarding light as particles, and the other of which treats light only as waves. Such a situation would be ludicrous in modern physics, yet it is exactly what we now confront in science as a whole.

Having said these things, I am now in the position of having to supply a positive model for science. I will try by suggesting that, just as in quantum physics, the truth about nature is to be found only by expanding the frame of discourse to include both of these complementary models of reality.

Two successful models of complementarity in serious scientific investigation may show what I mean. First, there is what began (and, as far as I know, is still regarded) as a dispute between Goethe and Newton over the nature of color. Both men developed theories of color: Newton's was purely quantitative; Goethe's dealt with the sensuous perception of color, including such phenomena as complementary colors and clashing colors. In a speech before the Society for Cultural Collaboration in Budapest in 1941, the German physicist Werner Heisenberg [who played a central role in the formulation of complementarity in quantum physics (*6*)] reviewed these two theories, especially the less familiar one of Goethe. Heisenberg clearly saw that the two are complementary, in that they are addressed to the same phenomenon from entirely different points of view. Yet, even for Heisenberg, Goethe's view had to be seen as in *opposition* to Newton's, and his verdict is rendered in language that is unfortunately characteristic of our approach to complementary realities (*15*):

> [The] battle is over. The decision on "right" and "wrong" in all questions of detail has long since been taken. Goethe's color theory has in many ways borne fruit in art, physiology, and esthetics. But victory, and hence influence on the research of the following century, has been Newton's.

Yet, if one asks himself "What is color?," the complete answer to such a question can be found only in the complementary descriptions from physics and art. To insist on projecting the question into one or the other of those separate worlds may be a good way to initiate research, but, at the same time, it distorts the original intention of the question.

The second area of nature in which complementary modes of learning have been applied, this time often by the same investigator, is in the study of animal behavior. Of many examples, the finest of which I am aware is George Schaller's study of gorillas (*16*). Here, in a beautiful whole, are a "serious" and straightforward account of the nature of the gorilla, and an account of Schaller's own presence in the forest—how he interacted with the gorillas and what he learned by observing the effects of this interaction. [In fact, Schaller's method was so far from the observation, by concealed experimenters, of captive animals in drab and sensuously meaningless mazes, cages, and boxes that it is inconceivable that his understanding of gorilla behavior is at all accessible to the orthodox animal psychologist (*17*).]

Implications for the Future of Science

At this writing, it seems beyond dispute that, for at least the next decade, the most important, active, and heavily funded field of science will be ecology—in its broadest sense. Unless we reach a full and effective understanding of human society and its place in the biosphere, there will be no science worth speaking of in the 21st century. It is lucky indeed that the generation born since 1950 is, as a group, deeply interested in all aspects of ecology. Yet this group will not use its energy and intelligence to seek scientific approaches to ecological problems until they are convinced that science is not "irrelevant" or, in fact, demonic.

What is urgently needed is a science that can comprehend complex systems without, or with a minimum of, abstractions. To "see" a complex system as an organic whole requires an act of trained intuition, just as seeing order in a welter of numerical data does. The conditions for achieving such perceptions have been discussed at length among scientists (with little discernible impact on the way we train scientists). The consensus, if any, is that they follow only after long periods of total immersion in the problem. The implication for the present discussion is that the intuitive knowledge essential to a full understanding of complex systems can be encouraged and prepared for by: (i) training scientists to be aware of sensuous clues about their surroundings; (ii) insisting on sensuous knowledge as part of the intellectual structure of science, not as an afterthought; and (iii) approaching complex systems openly, respecting their organic complexity before choosing an abstract quantification space into which to project them.

Because of the primitive, and even repressed, attitudes we now have (and pass on to our students) about intuitive knowledge and its transmission from one person to another, it is difficult to be more precise. Perhaps science has much to learn along this line from the disciplines, as distinct from the mystical content, of Oriental religions. If we do learn to know complexities through the complementary modes of sensuous intuition and logical abstraction, and if we can transmit and discuss the former as reliably as we do the latter, then there is hope for a renaissance in science as a whole comparable to that which occurred in physics between 1900 and 1930.

As usual, the bulk of the active and creative work in any such renaissance will fall to younger people: that is, to just those who, as a group, view the present posture of science as most suspect. Because the recruitment of each new generation of scientists takes place in the undergraduate colleges, I believe that the time is far overdue for a thorough restructuring of the way we educate scientists. Because higher education in Europe and the United States flourished along with the scientific revolution, its assumptions are largely those of science: that knowledge abstracted and codified into lectures and textbooks will stand for full knowledge (*18*).

In ex post facto response to the demands of our students (who may be only dimly aware of what is bothering them), we "inject" relevance into our teaching by means of examples that have been wrenched from their organic context and used to exemplify the abstractions that are the real matter of serious courses in science. I have gone so far, in my own teaching, as to sacrifice a few laboratory afternoons for my students to contemplate —without "lab sheets," ill-concealed hints about procedure, or even a demand that they keep and turn in a notebook—the colors, smells, textures, and changes of some substances on which they would do a rigorous and abstractly interpreted experiment the following week. In many instances, students have seen the connection and have become really excited about their dual insights into chemical systems. But even this is only a feeble fluctuation in the normal curriculum. Most of the students who go through it on their way to a degree are, at best, tolerant of my efforts to let them really know something about equilibria in aqueous solutions. At the risk of judging them too harshly, I cannot but feel that, by the time I see them, their natural curiosity about the physical world has been corrupted by too many years of rules, abstractions, and quickie true-false tests. And their fellows, who have awakened to the one-sidedness of the abstract worlds of scholarship in general and of science in particular, and have summarily rejected them, I never see at all.

I might address these remarks primarily to those who teach undergraduates. Yet there is no teacher of science who is not himself a scientist, and science as it is taught is allegedly a representation of science as it is practiced. If the practice of science continues its present one-sided and underdimensioned course, new scientists will be recruited predominately from among those people to whom such a view of the world is most congenial. Yet such people are least fitted, by temperament and training, to hold in mind the complementary truths about nature that our looming tasks will require. Indeed, one may seriously question whether even an underdimensioned science can be maintained as a creative enterprise by scientists recruited from among those of lesser imagination, sympathy, and humanity. Neils Bohr's vision of the unity of human knowledge only echoes, a half-century later, that of Walt Whitman: "I swear the earth shall surely be complete to him/or her who shall be complete. The earth remains jagged and broken to him/or her who remains jagged and broken."

References and Notes

1. L. White, Jr., *Science* **155**, 1203 (1967); L. W. Moncrief, *ibid.* **170**, 508 (1970); N. O. Brown, *Life Against Death: The Psychoanalytical Meaning of History* (Wesleyan Univ. Press, Middletown, Conn., 1959), chap. 16.
2. T. Roszak, *The Making of a Counter Culture* (Doubleday, Garden City, N.Y., 1969).
3. L. Mumford, *The Myth of the Machine: The Pentagon of Power* (Harcourt Brace Jovanovich, New York, 1970).
4. To some readers, "sensuous" may suggest genital sexuality. Although "unconventional" sexual morality is a feature of the counterculture (as it is of the technological one), I use the word in a more general sense: that is, the response of the whole body, including the senses, to phenomena. Usually, such a response is, of course, not susceptible to quantification. It is also dependent on subjective factors such as mood and attention, but it is undeniably a source of information about the world around us.
5. G. N. Lewis and M. Randall, *Thermodynamics and the Free Energy of Chemical Substances* (McGraw-Hill, New York, 1923).
6. W. Heisenberg, "Quantum theory and its interpretation," in *Neils Bohr: His Life and Work as Seen by His Friends and Colleagues*, S. Rozental, Ed. (Wiley, New York, 1967).
7. N. Bohr, *Atomic Physics and Human Knowledge* (Wiley, New York, 1958).
8. N. Bohr, in *Essays, 1958–1962, on Atomic Physics and Human Knowledge* (Wiley, New York, 1963).
9. C. P. Snow, *The Two Cultures and the Scientific Revolution* (Cambridge Univ. Press, New York, 1959).
10. J. Bronowski, *Science and Human Values* (Harper, New York, 1956).
11. E. Hobsbawn, "Is science evil?," in *New York Review of Books*, 19 November 1970.
12. A. N. Whitehead, *Science and the Modern World* (Macmillan, New York, 1925).
13. J. Bruner, *On Knowing: Essays for the Left Hand* (Harvard Univ. Press, Cambridge, Mass., 1962); J. Holt, *How Children Learn* (Pitman, New York, 1967); R. Jones, Ed., *Contemporary Educational Psychology: Selected Readings* (Harper, New York 1967).
14. J. Watson, *The Double Helix* (Atheneum, New York, 1968).
15. W. Heisenberg, *Philosophic Problems of Nuclear Science* (Pantheon, New York, 1952).
16. G. Schaller, *The Year of the Gorilla* (Ballantine, New York, 1965).
17. For a single research paper that nicely combines sensuous and mathematical descriptions of a phenomenon, see C. W. McCutchen [*Science* **170**, 61 (1970)].
18. Of course, we know that that isn't really true; we just act as if it were. And it takes no great perception on any teacher's part to see that most of his class don't really understand what they write back to us on examinations; perhaps that's why we are careful to set such examinations as soon as possible after the material is "learned."