The Significance of Science

Cultural and social aspects of science and its relation to society are discussed.

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And I gave my heart to seek and search out by wisdom concerning all things that are done under heaven. This sore task hath God given to the sons of man to be exercised herewith.—Ecclesiastes 1 : 13.

For in much wisdom is much grief and he that increaseth knowledge increases sorrow.—Ecclesiastes 1 : 18.

The development of science and technology during the last centuries has been very fast and overwhelming. All aspects of human society have been deeply influenced by it, the quality of life has been changed and often gravely disturbed. Today we have become very sensitive to the problems raised by this fast development, and we are faced with important questions regarding the role of science in society.

Science is under severe attack from some quarters; it is considered a panacea for the cure of all ills by others. I will sketch here three positions in regard to science that characterize some of the common attitudes toward this problem.

Position 1. Many branches of science have grown excessively during the recent decades; too large amounts of public support and too much scientific manpower are devoted to esoteric research in fields that have little to do with practical problems. Only such scientific research should be supported as that promising reasonable payoff in terms of practical applications for industry, public welfare, medicine, or national defense. Science as a study of nature for its own sake is appreciated by only a few people and has very limited public value. Its support should be reduced to a much more modest scale.

Position 2. Most of today's scientific research is detrimental to society because it is the source of industrial innovations, most of which have led and will lead to further deterioration of our environment, to an inhuman computerized way of life destroying the social fabric of our society, to more dangerous and destructive applications in weaponry leading to wars of annihilation, and to further development of our society toward Orwell's world of 1984. At best, science is a waste of resources that should be devoted to some immediate, socially useful purpose.

Position 3. The methods and approaches used in the natural sciences and in technology—the so-called scientific method—has proved overwhelmingly successful in resolving problems, in elucidating situations, in explaining phenomena of the natural world, and in attaining well-defined aims. It should be extended to all problems confronting humanity because it promises to be as successful in any area of human endeavor and human interest as it has been in the realm of natural science and technology.

These three positions are, to a large extent, mutually exclusive. They point in three almost orthogonal directions. In this essay I contend that each of these positions takes a narrow and one-sided view of the role of science in human society. Science is involved in man's thought and action in many different and often contradictory ways. Science must coexist with other forms of human urges, feelings, and self-realizations. Science is based on a very fundamental human urge: man's innate desire to know and understand the universe in which he lives and to gain insight into the driving forces that govern the world around us. This urge is paired with another one: the desire to improve the precarious conditions of human existence in a hostile world, in a hostile natural environment, and in hostile societies. Man desires to influence and to change the material and social conditions of life with the help of acquired knowledge and experience, which, in modern times, are mainly derived from science. As in all human situations, the urges and desires do not always lead to actions that serve the intended purposes, and the intended purposes are not always such that real benefits accrue for the people involved. These are the basic elements for our discussion of the role of science in human affairs.

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Basic Science and Practical Applications

Let us return to position 1, the excessive cost of basic science. It is based on the supposition that most of research is unimportant and irrelevant if it is carried out without regard to practical applications. It is commonplace that technology and medicine owe an enormous debt to the study of nature for its own sake, that is to basic science. It is hardly necessary to mention here the many instances which prove that modern industry and modern care for the sick are based on past results of basic science. Nor is basic science such an expensive luxury when its cost is compared with its services. The total cost of all basic science from Archimedes to the present day is probably near \$30 billion (*1*), less than 12 days' worth of production of the United States whose gadgets and machines are to a large extent the product of earlier scientific achievement. The practical value of those parts of pure science which seemingly have no immediate connections with applications has been clearly brought out by H. B. G. Casimir, who collected a number of interesting examples of how decisive technical progress was made by scientists who did not work at all for a well-defined practical aim (*2*):

> I have heard statements that the role of academic research in innovation is slight. It is about the most blatant piece of nonsense it has been my fortune to stumble upon.
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> Certainly, one might speculate idly whether transistors might have been discovered by people who had not been trained in and had not contributed to wave mechanics or the theory of electrons

in solids. It so happened that inventors of transistors were versed in and contributed to the quantum theory of solids.

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 thirties 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. Perhaps—only it didn't happen that way, and there were the Curies and Rutherford and Fermi and a few others.

One might ask whether an electronic industry could exist without the previous discovery of electrons by people like Thomson and H. A. Lorentz. Again, it didn't happen that way.

One might ask even whether induction coils in motor cars 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.

Some of these examples are evidences of the fact that experimentation and observation at the frontier of science require technical means beyond the capabilties of ordinary technology. Therefore, the scientist in his search for new insights is forced and often succeeds to extend the technological frontier. This is why a large number of technologically important inventions had their origin not in the desire to fulfill a certain practical aim but in the attempts to sharpen the tools for the penetration of the unknown.

The examples quoted are taken from past developments and it is frequently asserted that some branches of modern fundamental science are so far removed from the human environment that practical applications are most improbable. In particular, the physics of elementary particles and astronomy are considered to be in this category. These sciences deal with far-off objects; elementary particles in the modern sense are also "far off," because mesons and baryons appear only when matter is subject to extremely high energy which is commonly not available on Earth but probably occurs only at a few distant spots in the universe. The "far off" feature of these sciences is also what makes them expensive. It costs much money to create in our laboratory conditions that may be realized only in some exploding galaxy. It costs much to build instruments for the study of the limits of the universe. The argument against these sciences is that they are dealing with subjects far removed from our human environment and that therefore they are of minor relevance.

Let us consider the question of what constitutes the human environment. Ten thousand years ago there were no metals in the human environment. Metals rarely are found in pure form in nature. But after man had found out how to create them from ores, metals played an important role in our environment. The first piece of copper must have looked very esoteric and useless. In fact, man used it for a long time only for decorative purposes. Later, the introduction of this new material into man's ken gave rise to interesting possibilities that ultimately led to the dominant role of metals in his environment. In short, we have created a metallic environment. To choose another example, electricity appears rarely in nature in observable forms; for example, only in lightning discharges and in frictional electrostatics, which is not an important part of the human environment. After long years of research into minute effects, it was possible to recognize the nature of electric phenomena and then to find out what dominant role they play in the atom. The introduction of these new phenomena into the human world created a completely new electric environment in which we live today with 120-volt outlets in every wall. The most recent example is in nuclear physics. In the early days, prying into the problems of nuclear structure was considered a purely academic pursuit, directed only toward the advancement of knowledge concerning the innermost structure of matter. Rutherford said in 1933, "Anyone who expects a source of power from transformation of these atoms is talking moonshine." His conclusion was based on the same reasoning: The nuclear phenomena are too far removed from our human environment. True enough, apart from the rare cases of natural radioactivity, nuclear reactions must be artificially created at high cost with energetic particle beams. Most nuclear phenomena on Earth are man-made; they occur naturally only in the center of stars. Here again, the introduction of these man-made phenomena into our human world has led to a large number of interactions. Artificial radioactivity has revolutionized many branches of medicine, biology, chemistry, and metallurgy; the process of fission is an ever-increasing source of energy, for the better or the worse. Nuclear phenomena are now an important part of a new human environment.

These examples show the weakness of the argument that certain natural phenomena are too far removed to be relevant to the human environment. Natural laws are universal; in principle, any natural process can be generated on Earth under suitable conditions. Modern instruments did create a cosmic environment in our laboratories when they produced processes that do not ordinarily take place in a terrestrial environment. Astronomy and particle physics deal with previously unknown and mostly unexplained phenomena. There is every possibility that some of them one day could also be reproduced on Earth in some form or another and be applied in a reasonable way for some useful purpose. Today already some special medical effects have been found for pion beams, effects that cannot be brought about by any other means. Purcell (*3*) once said about the applicability of frontier fields such as particle physics: "In our ignorance, it would be presumptuous to dismiss the possibility of useful application as it would be irresponsible to guarantee it."

One cannot divide the different branches of science into those that are important for practical applications and others that are not. The primary aim of science is not application, it is gaining insights into the causes and laws which govern natural processes. But a better understanding of a natural process almost always leads to possibilities of influencing it, or of influencing other processes related to the one that was investigated. The further science developed, the more relations between seemingly unrelated processes were discovered. The study of the solar corona, a phenomenon far off the earth, may lead to a better understanding of the behavior of highly ionized gases in magnetic fields, a topic of great technological importance. These relations between pure and applied science are part of the many-sided involvement of science in all aspects of human endeavor, from the urge to know more about the environment to the desire to improve and to dominate it.

Basic Science and Today's Problems

Position 2 is the expression of an attitude that makes science bear the brunt of public reaction against the mounting difficulties of modern life. This is not the place to analyze the predicaments of modern civilization whose difficulties are related to the increased rate of technological expansion, a rate that today has seemingly reached a critical value in both time and space. With regard to time, the changes in our way of life are now so rapid that marked differences are observable within one generation. This is a new and unsettling phenomenon for mankind; the experiences of the older generation are no longer as useful as they once were in coping with the problems of today. With regard to space, the effects of technology on our environment are no longer small; the parts of the earth's surface, of the water, of the air, which are changed by man or could be destroyed by man are no longer negligible compared to those left untouched. These are unexpected and disturbing consequences with which we do not yet know how to deal.

Since technology, particularly the increasing rate of technological change, is based largely upon science, it is not surprising that science is blamed for its difficulties. An obvious reaction to this situation would be to declare a moratorium on science; this would supposedly stop technological innovation and give us time to settle the problems that are already with us, instead of creating new ones. Recent cuts in scientific support reflect this attitude to some extent. We intend to refute, not the facts on which position 2 is based, but the conclusions drawn from that position.

The call for a moratorium in science is based on its inexorable way of progressing; one discovery leads to many others, and it seems impossible to prevent the application of new discoveries to unintentionally destructive purposes and socially detrimental technologies. Must we conclude, therefore, that it is harmful to continue the search for further knowledge and understanding of the world in which we live? It would seem that this search should be valuable under any circumstances, since knowing less about the world should hardly be better than knowing more.

Ignorance is of no value in itself; cruelty of man against his fellow man or thoughtless exploitation of man and nature existed before the industrial revolution. To stop the growth of scientific knowledge would not prevent its abuses, but it would deprive us of finding new means for avoiding them and deprive us also of an important source of philosophical insight. New scientific knowledge is neither good nor bad. New knowledge usually leads to a better way of predicting consequences and sometimes also to an ability to do something that one could not do before. It will be applied for good or for bad purposes, depending on the decision-making structure of the society, just as in the case of any social and political measure. In this respect science and technology are not different from other human activities.

Today it is fashionable to emphasize the negative aspects of technological progress and to take the positive aspects for granted. One should remember, however, that medical science has doubled the average life span of man, has eliminated many diseases, and has abolished pain in many forms. It has provided the means of effective birth control. The so-called "green revolution" created the potential to eliminate starvation among all presently living people. This is a scientific-technical achievement of momentous significance, even though the actual situation is a far cry from what could be achieved. One should also remember the developments in transportation, construction, and power supply provided by modern technology and their great potentialities for improving the quality of life.

The trouble comes from the fact that, in too many instances, technology has not achieved that purpose. On the contrary, it has contributed to a definite deterioration of life. Medicine may have abolished pain, but modern weapons are producing wholesale pain and suffering. Medical progress has achieved a great measure of death-control which has caused a population explosion; the available means of birth control are far from being effectively used. The blessings of modern medicine are unevenly distributed; lack of adequate medical care for the poor in some important countries causes mounting social tensions. The green revolution produces ten times more food than before, but the distribution is so uneven that starvation still prevails in many parts of the globe; furthermore, the massive use of fertilizers causes eutrophication of many waters. Power production and the internal combustion engine as a means of transportation have polluted the atmosphere. Is it really impossible to avoid harmful effects when we apply our knowledge of natural processes for practical purposes? It should not be so.

There are two distinct sides to these problems: the social and political aspect and the technical aspect. In some instances the technical aspects do not pose any serious problems. The most important example is the use of technology for war or suppression. The only way to prevent the application of scientific results to the development of weapons is to reduce and prevent armed conflicts; certainly, this is a sociopolitical problem in which scientists and nonscientists should be equally interested, but it is not per se a problem of natural science. Other more benign examples are the problems of congested transportation, of city construction, and of some, but not all, of the problems of pollution. In these cases we know what causes the trouble and we know what measures can be taken to avoid it. But we don't know how to convince people to accept these measures. The problems are political and social. The natural scientists cannot help except by pointing out as clearly as possible what the consequences of certain actions or inactions will be. It is beyond the scope of this article to discuss whether it is possible to resolve these political and social problems. We take the only possible attitude in this dilemma: We assume that there will be a solution at some time, in some form, to some of these problems.

However, there are also many detrimental effects of technology of which the physical causes or the remedies are not known to a sufficient degree. Many detrimental effects of industrialization upon the environment belong in this category; among these are carbon dioxide production, long-range influences on atmospheric currents and on climatic conditions, the influence of urbanization on health, the problem of better means of birth control, and many more. Here science has enormous tasks to do in discovering, observing, and explaining unexplored phenomena, relations, and effects. The problems deal with our natural environment and therefore necessarily pose prime questions pertaining to natural science.

What role does basic science play in these efforts? One could conclude that the tasks are for applied science only and that research for its own sake, research that is not directed toward one of the specific problems, is not necessary. It may even be harmful since it takes away talented manpower and resources. This is not so. The spirit of basic research is composed of the following elements: an interest in understanding nature; an urge to observe, to classify, and to follow up observed phenomena for the sake of the phenomena themselves; a drive to probe deeper into a subject by experimenting with nature, by using ingenuity to study phenomena under special and unusual conditions—all in order to find connections and dependencies, causes and effects, laws and principles.

This attitude of basic research is necessary for the solution of today's pressing problems because it leads people to search for causes and effects in a systematic way, regardless of any ulterior aim. Many of today's troubles are caused by unforeseen consequences of human action on the environment, by interference with the natural cycle of events. The effects of accumulated technological developments are about to cover the entire surface of the earth. We face a complicated network of physical, chemical, and biological causes and effects, many of them only partially understood. Much painstaking basic research will be required before these problems can be tackled efficiently. If technical solutions are introduced before the conditions are thoroughly understood, one may well worsen the situation in the attempt to improve it.

Why is basic research needed for this kind of training? Why couldn't one train people directly by putting them to work on socially pressing problems? Those who ask these questions compare the situation with teaching Greek and Latin to youngsters in order to give them experience in learning foreign languages. The comparison is fallacious. Polanyi (*4*) has expressed the reason most lucidly:

> The scientific method was devised precisely for the purpose of elucidating the nature of things under more carefully controlled conditions and by more rigorous criteria than are present in situations created by practical problems. These conditions and criteria can be discovered only by taking a purely scientific interest in the matter, which again can exist only in minds educated in the appreciation of scientific value. Such sensibility cannot be switched on at will for purposes alien to its inherent passion.

There are two sides to the argument. One concerns the analysis of a situation, and the other concerns the search for ways to improve it. The attitude engendered by pure science is most conducive to getting a clearer picture of the facts and the problems that may have to be faced in coping with air pollution, the population explosion, or the effects of technical innovations upon our environment. In basic science the search is for phenomena and connections in all possible directions, whereas in applied science the search is directed toward a specific goal.

Furthermore, when new technical ideas are needed—and they will be needed—the attitude of basic science is that of looking more toward innovative ideas and less toward the application of known devices because the problems at the frontier are exactly those that cannot be solved with established methods. In basic research a pool of young men and women is formed who are accustomed to tackle unexplained phenomena and who are ready to find new ways to deal with them. They are trained to work under the most exacting conditions in open competition with the scientific world community. Instead of "environmentalists" we should train physicists, chemists, geologists, and biologists capable of dealing with the problems of environment.

Whenever large practical projects have been carried out under emergency conditions—projects that were apparently immensely difficult or impossible—scientists from basic fields have played a decisive role. In the past most of the examples have come from war-related projects, such as the development of radar or the atomic bomb. There is no doubt, however, that this kind of development can be transferred to more constructive problems. In fact, many basic scientists have made important contributions toward a solution of the arms control problem. Their activities have initiated the discussions that led to the halt of bomb tests. Today they are deeply involved in environmental problems.

Two qualifications are in order. Today's problems certainly will require the methods and results of natural science, but they cannot be solved by these methods alone. As was mentioned earlier, the problems are to a great extent social and political, dealing with the behavior of man in complicated and rapidly evolving situations. These are aspects of human experience to which today's methods of natural science are not applicable. Seen within the framework of that science, these phenomena exhibit a degree of instability, a multidimensionality for which our present scientific thinking is inadequate and to which such thinking must be applied with circumspection. There is great temptation to transfer the methods that were so successful in natural science directly to social or political problems. This is not possible in most cases. Different methods may be developed in the future. The social sciences are working hard at the task.

The second qualification concerns the need for scientists trained in basic science. We do not argue that only those trained in basic science can solve our problems to the exclusion of others. Far from it; a collaboration between all kinds of people is needed—basic and applied scientists, engineers, physicians, social scientists, psychologists, lawyers, and politicians. The argument submits that people trained in basic science will play an important and irreplaceable role. They are necessary, but not sufficient. But their necessity emphasizes the importance of keeping basic science activities alive.

To keep basic science vigorous is today much harder than it was in the past; it would be harder even if the financial support were as generous as before. The reason is quite natural; the world situation has become so serious that many scientists or potential scientists find it difficult to worry about some unexplained natural phenomena or undiscovered laws of nature when there are more immediate things to worry about. Some scientists feel that we are in an emergency situation and that we should stop basic science for the duration as we did during World War II. But the war lasted only 4 years for the United States, while the present crisis will endure for at least two decades. If we cripple basic science today, it will not be long before there will be no new generations of devoted young scientists for the tests that mankind must face in the future.

Limitations of Science

Another motivation for the antiscience attitude expressed by position 2 is connected with widespread critical view of science and the ways of thinking it fosters. In this view, science is considered as materialistic and inhuman, as an instrument of defining everything in terms of numbers and thus excluding and denying the irrational and emotive approach to human experience. Value judgments, the distinction between good and evil, and personal feelings supposedly have no place in science. Therefore, it is said, the one-sided development of the scientific approach has suppressed some most important and valuable parts of human experience in that it has produced an alienated individual in a world dominated by science and technology in which everything is reduced to impersonal data.

The foregoing arguments are diametrically opposite to the views expressed in position 3, which contends that the supposedly rational, inemotive approach of science is the only successful way to deal with human problems of all sorts. Many of today's trends against science are based on the feeling that the scientific view neglects or is unable to take into account some of the most important experiences in human life.

This widely held belief seems to be in contradiction to the claim of "completeness" of science, which is the basis of position 3. It is the claim that every experience—whether caused by a natural phenomenon or by a social or psychic circumstance—is potentially amenable to scientific analysis and to scientific understanding. Of course, many experiences, in particular in the social and psychic realm, are far from being understood today by science, but it is claimed that there is no limit in principle to such scientific insights.

I believe that both the defenders and the attackers of this view could be correct, because we are facing here a typical "complementary" situation (*5*). A system of description can be complete in the sense that there is no experience that does not have a logical place in it, but it still could leave out important aspects which, in principle, have no place within the system. The most famous example in physics is the complementarity between the classical description and the quantum properties of a mechanical system. The classical view of an atom is a little planetary system of electrons running around the nucleus in well-defined orbits. This view cannot be disproved by experiment; any attempt to observe accurately the position of an electron in the atom with suitable light beams or other devices would find the electron there as a real particle, but the attempt to observe it would have destroyed the subtle individuality of the quantum state which is so essential for the atomic properties. Classical physics is "complete" in the sense that it never could be proven false within its own framework of concepts, but it does not encompass the all-important quantum effects. There is a difference between "complete" and something we may call "all-encompassing."

The well-known claim of science for universal validity of its insights may also have its complementary aspects. There is a scientific way to understand every phenomenon, but this does not exclude the existence of human experiences that remain outside science. Let us illustrate the situation by a simple example: How is a Beethoven sonata described in the realm of science? From the point of view of physics, it is a complicated quasi-periodic oscillation of air pressure; from the point of view of physiology it is a complicated sequence of nerve impulses. This is a complete description in scientific terms, but it does not contain the elements of the phenomenon that we consider most relevant. Even a psychological study in depth of what makes the listening to these tone-sequences so exciting cannot do justice to the immediate and direct experience of the music.

Such complementary aspects are found in every human situation. There exist human experiences in the realms of emotion, art, ethics, and personal relations that are as "real" as any measurable experience of our five senses; surely the impact of these experiences is amenable to scientific analysis, but their significance and immediate relevance may get lost in such analysis, just as the quantum nature of the atom is lost when it is subject to observation.

Today one is rather unaccustomed to think in those terms because of the rapid rise of science and the increasing success of the application of scientific ideas to the manipulation of our natural environment in order to make the process of living less strenuous. Whenever in the history of human thought one way of thinking has developed with force, other ways of thinking become unduly neglected and subjugated to an overriding philosophy claiming to encompass all human experience. The preponderance of religious thought in medieval Europe is an obvious example; the preponderance of scientific thought today is another. This situation has its root in a strong human desire for clear-cut, universally valid principles containing the answers to every question. However, the nature of most human problems is such that universally valid answers do not exist, because there is more than one aspect to each of these problems. In either of the two examples, great creative forces were released, and great human suffering resulted from abuses, exaggerations and from the neglect of complementary ways of thinking.

These complementary aspects of human experience play an important role when science is applied to practical aims. Science and technology can provide the means and methods to ease the strain of physical labor, to prolong life, to grow more food, to reach the moon, or to move with supersonic velocity from one place to another. Science and technology are needed to predict what would be the effects of such actions on the total environment. However, the decisions to act or not to act are based on judgments that are outside the realm of science. They are mainly derived from two strong human motives: the desire to improve the conditions of life, and the drive for power and influence over other people. These urges can perhaps be scientifically explained by the evolution of the human race, but they must be regarded as a reality of human experience outside the scientific realm. Science cannot tell us which of the urges is good or bad. Referring to the first rather than the to the second urge, Archibald MacLeish has put this idea into verse: "No equation can divine the quality of life, no instrument record, no computer conceive it/only bit by bit can feeling man lovingly retrieve it."

The true significance of science would become clearer if scientists and nonscientists were more aware of the existence of these aspects that are outside the realm of science. If this situation were better appreciated, the prejudice against science would lose much of its basis and the intrinsic value of our growing knowledge of natural phenomena would be much better recognized.

Intrinsic Value of Science

Since the beginnings of culture, man was curious about the world in which he lives and eager to explain it. The explanations have taken different forms—mythologic, religious, or magic —and they usually encompass all and everything from the beginning to the end. About 500 years ago man's curiosity took a special turn toward detailed experimentation with nature. It was the beginning of science as we know it today. Instead of reaching directly at the whole truth in an explanation for the entire universe—its creation and present form—it tried to acquire partial truths in a small measure about some definable and reasonably separable group of phenomena. Science developed only when men began to refrain from asking general questions such as: What is matter made of? How was the universe created? What is the essence of life? Instead, they asked limited questions, such as: How does an object fall? How does water flow in a tube? Thus, in place of asking general questions and receiving limited answers, they asked limited questions and found general answers. It remains a great miracle, that this process succeeded, and that the answerable questions became gradually more and more universal. As Einstein said: "The most incomprehensible fact is that nature is comprehensible."

Indeed, today one is able to give a reasonably definite answer to the question of what matter is made of. One begins to understand the essence of life and the origin of the universe. Only a renunciation of immediate contact with the "one and absolute truth," only endless detours through the diversity of experience could allow the methods of science to become more penetrating, and their insights to become more fundamental. It resulted in the recognition of universal principles such as gravitation, the wave nature of light, the conservation of energy, heat as a form of motion, the electric and magnetic fields, the existence of fundamental units of matter, the living cell, the Darwinian evolution. It reached its culmination in the 20th century with the discovery of the connections between space and time by Einstein, the recognition of the electric nature of matter and of the principles of quantum mechanics; the 20th century yielded some answers of how nature manages to produce specific materials, qualities, shapes, colors, and structures, and gave rise to new insights into the nature of life as a result of the development of molecular biology. A framework has been created for a unified description and understanding of the natural world on a cosmic and microcosmic level, and its evolution from a disordered hydrogen cloud to the existence of life on our planet. This framework allows us to see fundamental connections between the properties of nuclei, atoms, molecules, living cells, and stars; it tells us in terms of a few constants of nature why matter in its different forms exhibits the qualities we observe. The scientific insight is not complete, it is still being developed; but its universal character and its success in disclosing the essential features of our natural world makes it one of the great cultural creations of our era.

As part of our culture it has much in common with the arts; new forms and ideas are created in order to express the relations of man to his environment. However, the influence of science on society and on our lives and our thinking is much greater today in the positive and negative sense. There were times in the past in which the arts had a similar influence. Science is a unique product of our period.

Science differs from contemporary artistic creations by its collective character. A scientific achievement may be the result of the work of one individual, but its significance rests solely on its role as a part of a single edifice erected by the collective effort of past and present generations of scientists. This effort was and is made by scientists all over the world; the character of the contributions does not reflect their national, racial, or geographic origin. Science is a truly universal human enterprise; the same questions are asked by all men involved in science, the same joy of insight is experienced when a new aspect of deeper coherence was found in the fabric of nature. The choices of problems and the directions of research at the frontier of fundamental science depend much less on the economic, social, and political needs than most people assume; they are determined mainly by the instrumental possibilities of observation and by the internal logics of fundamental science itself. This is not so in applied science and technology which obviously are much more—though not completely—subject to societal demands of all kinds. The rapid developments of applied electronics and acoustics during World War II were certainly determined by military needs. But there are exceptions on both sides. The progress in nuclear physics and in plasma physics—these are to a large extent fundamental branches—was certainly much accelerated by the possibilities of practical applications to power production by nuclear fission or fusion. The invention of the transistor—an example of applied physics—was not prompted by its practical potentialities.

It is often difficult to distinguish between fundamental and applied science, and any considerations of this kind can lead to dangerous oversimplifications. The success of basic research derives to a large extent from the close cooperation of basic and applied science. This close relation provided tools of high quality, without which many fundamental discoveries could not have been made.

Compared to other groups the scientific community is more international or, better, more supranational because it transcends national and political differences. Personal contacts across borders are established easily between people working on similar problems; science has its own international language. The percentage of foreigners in scientific laboratories is probably greater than in any other human activity; there are some very successful international laboratories, among which CERN in Geneva stands out in the field of high-energy physics, as a model for the future United States of Europe. The international ties of science have been helpful even in nonscientific affairs; for example, in the so-called Pugwash conferences, scientists initiated a number of actions directed toward a more unified world, such as the ending of atomic bomb tests in the atmosphere and the beginning of serious talks on arms control.

Science has a peculiar relation to the traditional and the revolutionary. It is both traditional and revolutionary at the same time. Newton's mechanics and the electrodynamics of Faraday and Maxwell are still valid and alive. Current calculations of satellite orbits and of radio waves are still based on them. Revolutionary concepts, such as that of relativity and quantum theory did not invalidate the earlier ideas; they establish unexpected limitations to the old ideas, which remain valid within these limitations. On the other hand, there is a strong trend in science toward the new and the different. Technological advances and novel ways of thinking are constantly introduced to change the manner of working and the method of approach. But scientific revolutions are extensions rather than replacements. Apart from a few notable exceptions, old ideas are expanded and reinterpreted on a more universal basis. Old methods are proved not wrong, but impractical and inaccurate.

In many ways, the attitude of mind in science is opposed to some of the negative and destructive trends in today's thinking. It means being involved in activities where there is real progress; deeper and deeper insights into the natural world are continually obtained. It engenders a feeling of participation at a unique collective enterprise, the construction and improvement of a vast intellectual edifice, one of the great creations of contemporary culture. There is little dispute among scientists regarding the general value scale as to what is significant and as to the directions in which to proceed, although there are differences of opinion regarding the relative importance of different elements.

Scientific knowledge leads to an intimate relation between man and nature, to a closer contact with the phenomena derived from a deeper understanding. To know more about the laws and the fundamental processes on which the material world is based should lead to a deeper appreciation of nature in all its forms. It should show how natural events are closely interwoven and depend on each other, how almost every mineral structure and certainly every manifestation of life are unique and irreplaceable. Thus, science establishes an awareness of how the universe, the atom, and the phenomena of life coexist and are all one. It is ecology in its widest interpretation.

There are still many fascinating problems and unanswered questions at all frontiers of science. We are not yet skillful enough to deal with complexity in nature. Even the structure of liquids is not well understood. No physicist would have predicted the existence of a liquid state from our present knowledge of atomic properties. The complexity of living matter presents far greater problems. In spite of the growing insight into the fundamental processes of reproduction and heredity, we still know very little about the development of organisms, about the functioning of the nervous system, and we know practically nothing about what goes on in the brain when we think or when we use the memory. The deeper we penetrate into the complexities of living organisms, into the structure of matter, or into the expanses of the universe, the closer we get to the essential problems of natural philosophy: How does a growing organism develop its complex structure? What is the significance of the particles and subparticles of which matter is composed? What is the origin of matter? What is the structure and the history of the universe at large?

The urge to find answers to questions of the nature of life and matter and to pursue the search for laws and meaning in the flow of events is the mainspring and the most important justification of science. These problems may have little to do with the immediate needs of society, but they will always be in the center of interest because they deal with the where, whence, and what of material existence.

Obligations of the Scientist

Does the actual science establishment correspond to the ideal picture of science as we have drawn it? It certainly does not appear so to many observers outside of the scientific community and even to some scientists. The human problems caused by the ever-increasing development of a science-based technology are too close and too threatening; they overshadow the significance of fundamental science as a provider of deeper insights into nature. The scientist must face the issues raised by the influence of science on society. He must be aware of the social mechanisms that lead to the specific uses and abuses, and he must attempt to prevent the abuses and to increase the benefits of scientific discoveries. Sometimes he must be able to withstand the pressures of society toward participation in activities which he believes to be detrimental. This is not an easy task since the problems are to a great extent of social nature, and the motivations are often dictated by material profit and political power. It puts the scientist in the midst of social and political life and strife.

On the other side, the scientist also has an obligation to be the guardian, contributor, and advocate of scientific knowledge and insight. This great edifice of ideas must not be neglected during a time of crisis. It is a permanent human asset and important public resource. The scientist who devotes his time to the solution of our social and environmental problems does an important job. But so does his colleague who goes on in the pursuit of basic science. We need basic science not only for the solution of practical problems, but also to keep alive the spirit of this great human endeavor. If our students are no longer attracted by the sheer interest and excitement of the subject, we were delinquent in our duty as teachers. We must make this world into a decent and livable world, but we also must create values and ideas for people to live and to strive for. Arts and sciences must not be neglected in times of crisis; on the contrary, more weight should be given to the creation of aims and values. And it is a great value to broaden the territory of the human mind by studying the world in which we live.

Much can and should be improved in the style and character of scientific teaching and research. The rapid increase of science activities during the 1950's and 1960's has left its mark on scientists and science students. Some of the positive aspects have been adulterated; in many respects, science has become an organization for producing new results as fast as possible. Changes and new perspectives are in order. One of the most dangerous aspects in today's scientific life is overspecialization. There are several trends that lead to it. One is the increasing pace of research, which does not allow the researcher enough time to be interested in other fields not directly related to his own. He has enough trouble in trying to stay ahead of his numerous competitors in his own field and cannot devote much time to anything else. Another impetus has been the general availability of research jobs in all fields; therefore the young scientist did not see the necessity of training himself in fields outside his speciality. Our educational system did not produce "physicists," it produced high-energy physicists, solid-state physicists, enzyme biochemists, and so forth. A typical symptom of this disease can be found in the manpower questionnaire that the National Science Foundation circulated among physicists, where one is asked to specify one's field which is subdivided to the extreme. For example, there are divisions of this kind: elementary particles, hadrons; elementary particles, leptons; solid-state, magnetic properties; solid-state, optical properties. . . . And people try to find a job in exactly the sub speciality of their Ph.D. thesis. What a narrow view and what a boring life with the same subfield of physics forever! A physicist should be interested in all of physics and should welcome a change of field. Most of the positive aspects of science come from an awareness of its broad range, of its universal view. The same quantum theory governs elementary subparticles and phonons or excitons in a solid.

The teaching of science must return to the emphasis on the unity and universality of science, and should become broader than the mere attempt to produce expert craftsmen in a specialized trade. Surely, we must train competent experts, but we also must bring fields together and show the connections between different fields of science. This task may be difficult because of heavy demands on the time and the intellectual capacities of those involved in modern research. But it is highly rewarding from any point of view. The teacher will get a deeper satisfaction from his work and the student will enjoy his studies more; his knowledge will be broader, it will help him in his future work, and he will have a wider choice of jobs.

I. I. Rabi says so succinctly (*6*):

> Science itself is badly in need of integration and unification. The tendency is more the other way . . . . Only the graduate student, poor beast of burden that he is, can be expected to know a little of each. As the number of physicists increases, each specialty becomes more self-sustaining and self-contained. Such Balkanization carries physics, and, indeed, every science further away from natural philosophy, which, intellectually, is the meaning and goal of science.

A broader understanding of science as a whole, beyond professional specialization, is a necessary condition for fostering the attitude toward nature, which should be the basic philosophy of a scientist. It is that attitude of intimacy with the universe, with its richness and its uniqueness, the feeling of special responsibility toward nature here on Earth, where we have power over it, constructive and destructive. The deeper understanding of nature as a whole leads to a duty on the part of the scientific community to be watchful and to warn against intentional and nonintentional misuse of science and its applications.

Another destructive element within the science community is the low esteem in which clear and understandable presentation is held. This low esteem applies to all levels. The structure and language of a scientific publication is considered unimportant. All that counts is the content; so-called "survey" articles are understandable only to experts; the writing of scientific articles or books for nonscientists is considered a secondary occupation and, apart from a few notable exceptions, is left to science writers untrained in science, some of whom are excellent interpreters. Something is wrong here. If one is deeply imbued with the importance of one's ideas, one should try to transmit them to one's fellows in the best possible terms.

In music, the interpretive artist is highly esteemed. An effective rendering of a Beethoven sonata is considered as a greater intellectual feat than the composing of a minor piece. We can learn something here: Perhaps a lucid and impressive presentation of some aspect of modern science is worth more than a piece of so-called "original" research of the type found in many Ph.D. theses, and it may require more maturity and inventiveness. Some students may derive more satisfaction from an interpretive thesis—and so may some readers.

Furthermore, the scientist helps himself by attempting seriously to explain his scientific work to a layman or even to a scientist in a different field. Usually, if one cannot explain one's work to an outsider, one has not really understood it. More concerted and systematic effort toward presentation and popularization of science would be helpful in many respects; it would provide a potent antidote to overspecialization; it would bring out clearly what is significant in current research, and it would make science a more integral part of the culture of today.

Much more could and should be done to bring the fundamental ideas nearer to the intelligent layman. Popularization of science should be one of the prime duties of a scientist. The most important instrument for spreading the spirit of basic science is education. Young people should become more familiar with the insights into the workings of nature which our age has revealed. There is more to it than the mere teaching of science. Scientific education must include active involvement in research. Students can absorb the spirit of science only if they face unsolved problems, participate in the process of analyzing facts, sift evidence, construct and test new approaches and ideas. Even at the lower levels, in elementary and high school, science activities should play an increasing role. Intelligent play involving simple natural phenomena fosters a deeper appreciation of our natural environment and transmits the joy of discovery. Margaret Mead (*7*) expressed it most impressively:

> Any subject, no matter how abstract, how inanimate, how remote from the ordinary affairs of men, remains lively and growing if taught to young children who are themselves growing by leaps and bounds, hungering and thirsting after knowledge of the world around them. To children, an understanding of the world around them is as essential as the tender loving care that, during this century, has been so exclusively emphasized in discussions of early childhood education. The language of science will then become—for everyday use—a natural language, redundant, wide in scope, deeply rooted in many kinds of human experience and many levels of human abilities.

Epilogue

Science is involved with society in many respects. There is a broad spectrum of relations—philosophic, social, and ethical—by which science influences and is influenced by society. The significance of science becomes evident in the numerous, often contradictory, aspects in which it interacts with the affairs of men.

The philosophic significance is derived from the progressively deeper and more comprehensive insight into the workings of nature. The edifice of ideas that brought about this understanding of nature was erected during the last 300 years and is one of the most sophisticated systems of thought ever constructed by man. Its great power resides in the essential simplicity of the fundamental concepts. The infinitely complicated variety of phenomena seems to emerge from a few simple, though subtle, laws of nature.

The social significance derives from the increasing ability to change our environment and the quality of life by applying the results of science. The changes have been both beneficial and detrimental, depending on the wisdom and intentions of those who carried them out. They have had deep and lasting effects on the social structure of society. The ethical significance derives from the recognition that the evolution of life and men on Earth is predicated on a most precarious equilibrium of physical conditions on this planet. From this recognition follows a human responsibility to protect and continue the great experiment of nature which required several billions of years to get under way. Science emphasizes the unity of human beings in the urge to gain rational understanding of the workings of nature, and in the task of caring for their natural environment. It brings people together in the search for deeper insights, on a front which to a large extent remains uninfluenced by the political and social divisions.

Science claims universality. All phenomena and all human experiences are supposed to fit into the context of natural laws and have found or will probably find a scientific description or explanation. However, the scientific interpretation of human experiences does not always shed light on those aspects that are often considered most relevant. These aspects include human emotional experiences, such as feelings and value judgments. They are decisive in the realm of human decision-making. Whenever a choice is made between actions, whenever collective or personal decisions are taken, scientific reasoning can and should provide information about predictable consequences. The actual decision, however, remains outside of science, it represents a kind of reasoning which necessarily is complementary to scientific thought.

Science contains many activities of different aims and different character—the several basic sciences with all their variety of approach from cosmology to biology and the numerous applied sciences that are spreading and involving more and more aspects of human concerns. Science is like a tree in which the basic sciences make up the trunk, the older ones at the base, the newer, more esoteric ones at the top where growth into new areas takes place. The branches represent the applied activities. The lower, larger ones correspond to the applied sciences that emerged from older basic sciences; the higher, smaller ones are the outgrowth of more recent basic research. The top of the trunk, the frontier of basic research, has not yet developed any branches. Applying this picture to the physical sciences, we would locate classical physics, electrodynamics, and thermal physics at the lowest part of the trunk with broad branches representing the vast applications of these disciplines. Higher up the trunk we would put atomic physics with well-developed branches such as chemistry, materials science, electronics, and optics. Still higher we would find nuclear physics with its younger branches symbolizing radioactivity, tracer methods, geology, and astrophysical applications. At the top, without branches, so far, we would locate modern particle physics and cosmology. There was a time, only 50 years ago, when atomic physics was the branchless top.

All parts and all aspects of science belong together. Science cannot develop unless it is pursued for the sake of pure knowledge and insight. But it will not survive unless it is used intensely and wisely for the betterment of humanity and not as an instrument of domination by one group over another. There are two powerful elements in human existence: compassion and curiosity. Curiosity without compassion is inhuman; compassion without curiosity is ineffectual.

References and Notes

1. This figure is based upon an exponential increase of expenditure with a doubling time of 10 years, as it occurred during the last two decades, and a final yearly expenditure of $3 billion. The starting time is irrelevant.
2. From a contribution by H. B. G. Casimir at the Symposium on Technology and World Trade, National Bureau of Standards, U.S. Department of Commerce, 16 November 1966.
3. E. Purcell, quotation from an unpublished report to the Physics Survey Committee of the National Research Council, Washington, D.C.
4. M. Polanyi, *Personal Knowledge* (Univ. of Chicago Press, Chicago, 1958), p. 182.
5. Similar views have been expressed by T. R. Blackburn [*Science* **172**, 1003 (1971)].
6. I. I. Rabi, *Science: The Center of Culture* (World, New York, 1970), p. 92.
7. M. Mead, *Daedalus* **88**, 139 (1959).

NEWS AND COMMENT

National Environmental Policy Act: How Well Is It Working?

In a moment of jubilation, shortly after Congress passed the National Environmental Policy Act (NEPA), which he coauthored in 1969, Senator Henry M. Jackson acclaimed the new law as the "most important and far-reaching conservation measure ever enacted." It will be some time, of course, before anyone can fairly judge whether the law actually has lived up to Senator Jackson's description. But at the 2-year mark, NEPA has clearly established itself as one of the most controversial environmental measures of all time—one whose repercussions have rattled virtually every department and bureau of the federal government in a remarkably short time.

The law has two major features. One establishes the President's three-man Council on Environmental Quality (CEQ), which is partly responsible for encouraging the government to comply with NEPA and partly for advising the President on environmental affairs. The other feature is a broad statement of policy to the effect that government should seek to enhance the environment "by all practical means" consistent with other national policies, and that every citizen should help. What lends muscle to the lofty intentions of NEPA is an "action-forcing" provision that requires government administrators to prepare detailed statements of the environmental effects of any major action they propose, and to study all practical alternatives.

This "action" proviso is at the focal point of the controversy over NEPA and has led to efforts by some agencies to seek legislative exemptions from the law. These efforts, and the court rulings that led to them, were described in an article last week; this article deals with NEPA's more pervasive day-to-day effects on the government.

Is NEPA, in fact, producing useful results? The law's success, to a great extent, is in the eye of the beholder. Unquestionably, the law has given both community and national environmental groups a substantial new access to the courts, and, in turn, their litigation has given NEPA a forceful clout that it might never have had otherwise. The most visible offspring of this symbiotic union has been a series of federal court rulings that have dealt some stunning setbacks to major programs of the Atomic Energy Commission (AEC), the Department of the Interior, and even the Environmental Protection Agency—all of which inspires one environmental lawyer in Washington to call NEPA "the great equalizer."

Like the pistol of the same name, NEPA has also engendered a certain amount of ill-will, particularly among congressmen from districts where public works have been held up for court-ordered environmental reviews, as well as among a growing number of government administrators whose programs have been paralyzed by similar court rulings. Several observers of the new law's evolution detect a strong undercurrent of resentment toward NEPA among such mid-level officials, who