THE SIGNIFICANCE OF CHEMISTRY

To Man in the Modern World

A proposed program for the education of the citizen in science, which would start at the kindergarten level

by LINUS PAULING

IT IS IMPOSSIBLE TO DENY that science has played a major part in determining the nature of the modern world. The food that we eat, the clothes that we wear, the means of transportation that we use in going from place to place, the medicines that keep us well, the weapons that we use in killing each other have all been changed in recent years through scientific discovery.

It may well be contended that the world is now in a dangerous situation because science and its applications have developed faster than the understanding of the average citizen. It is evidently of great importance to attempt to improve this situation through a program of education of the citizen in science. The world in modern times has continued to move toward the ideal democratic system, in which all important decisions are made by the people as a whole. In order for this system to operate correctly the citizen must have knowledge enough of the world to make the right decisions; and in the modern world this means that the citizen must have a significant understanding of science.

Nearly everyone has some knowledge about science in the modern world. We know that stockings used to be made from silk, a fiber spun by the silkworm, and are now made in large quantities from an artificially spun fiber, nylon. We know that penicillin, a substance made by a mold, is a very effective medicine for protecting us against bacterial infection, and that chloramphenicol and aureomycin are effective even against some of the virus diseases. We know that power can be transported from one place to another by the flow of electricity along wires, and that this flow of electricity is in fact the movement of charged elementary particles, electrons, along the atoms that constitute the wire. We know that, through the advance of physics during the last half century, man has discovered how to release the immense amounts of energy that are stored up in the nuclei of atoms; and we know that this knowledge is being used in the manufacture of atomic bombs. We know that uranium and thorium could be used to generate electric power, through the release of the energy stored up in the nuclei of the uranium and thorium atoms, and that the known deposits of minerals containing these elements could provide all of the energy required for the world, at the present rate of use, for thousands of years.

It is evident that these are important facts, that contribute to the determination of the nature of the modern world. In order to get an idea of how important science is to the modern world, we might ask how many scientific facts are now known, in comparison with the number of non-scientific facts. How great a fraction of all of the knowledge possessed by man is now scientific knowledge?

It is impossible to answer this question precisely, because we have no scale for measuring the comparative importance of a scientific fact and a non-scientific fact. Nevertheless, it may be of interest to consider the rate at which our store of scientific knowledge is being increased. During the year 1949 the journal *Chemical Abstracts*, which attempts to review all of the current publications in chemistry and closely related fields, contained abstracts of 70,000 papers in the field of chemistry. Many of these papers report only one contribution to knowledge, which might be described as one new scientific fact. Some of them report two or more contributions to knowledge that might be described as separate new scientific facts—the subject index of *Chemical Abstracts* for 1949 lists 220,000 items. I believe that we may say, as a rough approximation, that about 100,000 new chemical facts are being discovered each year, at present. Perhaps we may multiply this number by 10, to include other sciences as well as chemistry, and thus reach the rough conclusion that about one million new scientific facts are being discovered each year.

How many significant non-scientific facts are added to man's body of knowledge each year? A non-scientific fact may be a historical event, an artistic creation, a historical, economic, or social correlation, a new general idea published in a paper or book. It is, of course, impossible to define a non-scientific fact rigorously in such a way as to be equivalent to a scientific fact. Nevertheless, we might attempt to estimate how many significant, non-ephemeral items of new non-scientific information we have about the world, at the end of 1949, that we did not have at the beginning of the year. It seems to me that the number of these non-scientific facts may well be much less than one million; and that we may accordingly be justified in saying that scientific knowledge is at least roughly equivalent in its significance to the modern world to non-scientific knowledge, at the present time.

Chemistry and the Average Man

The average citizen has a much better understanding of the non-scientific aspects of the modern world than of its scientific aspects. His knowledge has been obtained in part through his studies in school, and in part through his reading and personal experiences. The great mass of people have not had education extending beyond the elementary school, and have accordingly received no instruction in science at all, or at most one or two years of instruction, in geography and general science. The nature of science is such that it is difficult for a man to begin its study without help; accordingly those people, constituting the great mass of the people in the world, who have not studied science in any form in school in general remain ignorant of science throughout their lives, except to the limited extent that scientific information is provided by personal experience.

Because of the nature of chemistry, the average man knows less about chemistry than about other sciences. He knows about many physical phenomena through his own observation—he knows that objects fall toward the earth, that hot bodies emit light and heat, that an electric spark may pass between two conductors at different potentials, that a body continues to move in a straight line unless acted on by some force (he may recognize that the curved path followed by a projectile reflects the effect of the gravitational attraction of the earth on the projectile), and so on. With this knowledge from personal experience, he is able to understand simple explanations of new discoveries in the field of physics, and to appreciate their significance to him and to the world as a whole. Similarly, he has had personal experience with phenomena in the field of biology, geology, medical sciences, mechanical technology, and other fields, which permit him to develop an increased understanding of their nature and their significance in the modern world. His personal experiences with chemical phenomena may, however, be very limited—be limited perhaps to the observation of the chemical reactions that occur in combustion. Chemical phenomena, involving the conversion of substances into other substances, which may have entirely different properties, are so surprising in their nature that it is difficult for a man to develop an appreciation of them without instruction. The average man accepts the facts of chemistry that are significant to him, such as the combustion of gasoline with oxygen in an engine to produce mechanical power, as wonders that are not to be understood; and it is not surprising that he may occasionally be led to believe that some new device, offered for sale to him, can be attached to his automobile engine to permit water to be used as fuel in place of gasoline.

This example illustrates one way in which increased scientific knowledge is of value to man in the modern world. The welfare of the individual is determined in considerable part by the decisions that he makes about his own actions; in general, by the way he spends his money. Much of his money is spent in response to advertising appeals that are based on his understanding or misunderstanding of science. The principle of caveat emptor has become far more dangerous to the citizen than it was in the simple, non-scientific world of past centuries. The citizen is asked to buy products containing ozium, arium, durium—and he is not told what these substances (if they are substances, and not just names) are. Ozium is to be sprayed around within the house, to kill all insects, destroy all cooking odors, protect against disease by killing germs too. Presumably the name ozium was selected because of the hope that the reader of the advertisement would confuse it with ozone, about whose germicidal properties he might have heard. He is asked to buy wonderful new green medicines, containing chlorophyll. Whatever substances, perhaps effective, may be present in the medicines, the advertiser counts on the chlorophyll to sell them. He is banking on the possession of a smattering of scientific information by the reader—and on his lack of possession of more than a smattering. He hopes that the reader will remember that chlorophyll is the wonderful substance in the leaves of green plants, that purifies the air. He hopes that the reader does not know much more—that he does not know that the only thing that chlorophyll is known to do is to absorb carbon dioxide from the air and to liberate oxygen; and that chlorophyll that has been extracted from the plant has, so far as any scientist has been able to discover, no action as a medicine, no activity whatever. Moreover, he must be hoping that the reader of the advertisement will not even think enough to ask why he does not eat a green leaf, a small spoonful of cooked spinach, or other green vegetable, in order to get his chlorophyll, instead of paying a hundred times as much money for inactive chlorophyll in a pill.

In this, and in many similar ways, it is of individual importance to the citizen in the modern world to have an increased understanding of the scientific aspects of the world.

The citizen who is trained in science may also be expected to exercise his political rights more effectively than one not trained in science, both because of his greater understanding of the nature of the modern world and because of his understanding of the scientific method, the way in which conclusions can be drawn from facts. Understanding of the scientific method confers on him the scientific attitude, which gives him an increased chance of reaching the right decision about political and social questions as well as about scientific questions.

One value of training in the scientific method is that it leads to skepticism about all generalizations, "laws of nature." What do we mean by a law of nature? We mean that a number of facts have been seen to be related to one another in such a way as to justify a general statement. For example, when chemical analysis of water was first made it was found that the sample of water that was analyzed contained 11.2% hydrogen and 88.8% oxygen. When another analysis was carried out, with another sample of water, the same result was obtained, and after a hundred analyses had been made—perhaps after only ten had been made—the general law was proposed that all samples of water contain 11.2% hydrogen by weight. This law was accepted for many years; but finally an analysis was made that showed that the percentage of hydrogen in rain water is a little less than 11.2%, and the percentage in ocean water is a little greater. This new observation then required that the earlier law of nature be changed, in such a way as to take into account the existence of isotopes of hydrogen and oxygen, and the fractionation of water molecules containing different isotopes through the process of evaporation of water from the ocean. A scientific law that is based on only ten facts which agree with one another is not considered to be a very sound one—it has only a limited probability of continuing to remain valid, as more experiments are made. A law that is based on a hundred facts, or a thousand, has greater and greater probability of continuing to be correct. A citizen who understands the nature of scientific generalizations will ask himself what the basis is for generalizations in the field of economics, politics, international relations. How many facts have been used in determining the attitude of one nation toward another nation? Is the number of facts in agreement with one another in supporting the attitude so great that there is no room whatever for skepticism about the national policy on the part of an individual citizen ,or is the citizen justified in being skeptical?

The Laws of Probability

The laws of probability have as much significance in non-scientific fields as in scientific fields. We all understand how a life insurance company calculates its premium payments. The statistician for the life insurance company collects information about the number of people dying at various ages—30, 31, 32, 40, 50, 60, 70, 80, 90, 100, even 110 years of age. From all of these data he calculates the average expectancy of life, and thus finds the average number of premiums that will be paid. If he were to say "It is abnormal for a man to live to be 85 years old, or older; therefore I must discard the data about these abnormal people" he would obtain a wrong value about the average expectancy of life, and the life insurance company would go bankrupt. Yet, just this foolish procedure is sometimes carried out in the operation of a democratic system of government. The principle upon which a true democratic system operates is that no single man is wise enough to make the correct decisions about the very complex problems that arise, and that the correct decisions are to be made by the process of averaging the opinions of all of the citizens in the democracy. These opinions will correspond to a probability distribution curve, extending from far on the left to far on the right. If, now, we say that all of the opinions that extend too far to the right—beyond the point corresponding to the age 85 in the above example, say—are abnormal, and are to be excluded in taking the average, then the average that we obtain will be the wrong one. An understanding of the laws of probability would accordingly make it evident to the citizen that the operation of the democratic system requires that every one have the right to express his opinion about political questions, no matter what the opinion might be.

It is of the greatest importance to modern man that he understand the modern world. He must have knowledge enough about the world to make the right decisions—and since the modern world is largely scientific in its constitution, the citizen must understand science.

How can the citizen get scientific knowledge? The answer to this question can be drawn from past experience. Hundreds of years ago it was recognized that mathematics is of great value to the individual. Mathematics is a difficult subject; one might be tempted to say that, since it is difficult, the study of it should be put off till the college years. Yet, through experience, we have learned that the way to teach mathematics is to start with the teaching of numbers in kindergarten, arithmetic in the first grade and other elementary grades, and to continue steadily, without interruption, through algebra, geometry, trigonometry, calculus. This is the way in which science should be taught.

Science in the Kindergarten

The time has now come for the study of science to be made a part of the curriculum in every grade, at every level. There should be a class in science in the kindergarten, in the first grade, in the second grade, in the third grade, and so on. Every boy and girl who finishes grammar school should know science, in the same way that he now knows arithmetic, languages, and history. Every boy and girl who finishes high school should know still more about science. Every college student should begin his college work with a sound knowledge of the whole of science—comparable to the knowledge that he now has, at this stage, of mathematics—in order that he might devote his years in college to the more advanced aspects of the subject. Only in this way can we train citizens for life in the modern world. Only in this way can we develop a citizenry able to solve the great social and political problems that confront the world.

In suggesting that the study of science should be carried on throughout the period of school training, I have in mind that it should occupy one class hour every day—that is, one instructional period of thirty or forty minutes in the beginning grades, and forty or fifty minutes in the higher grades. At the present time in many primary schools elementary instruction is given in geography, usually at some time between the fourth and the eighth grade. In addition, it is customary in many parts of the world for a course lasting for one year to be given in general science, usually the last year of primary school work, the eighth grade. In a relatively few schools a small amount of information about the nature of the physical and biological world is presented to the students during the first few years of primary school work. If one classroom period per day were devoted to science throughout the years of primary school instruction, the work might begin with very simple discussions of the physical world, including simple demonstrations. The fields of knowledge covered would be largely descriptive in nature, in all branches of science—physics, chemistry, biology, geology, astronomy, geography, etc.; but in addition there could be, even in the earliest years, instruction in the scientific method and the scientific attitude.

Understanding Certain Scientific Concepts

The concepts of chemical change and of atomic structure and other concepts of modern science are no more difficult to understand than the concept that the earth is round. We teach students in the elementary schools that the earth is round, even though convincing proof is so difficult that the fact has been generally accepted only during the last few centuries. In the same way the important basic principles of atomic science could now be taught to beginning students, in the elementary schools, with rigorous proof of the truth of the concepts deferred until a later time.

The principal practical problem accompanying the introduction of instruction in science for one class period each day in all school grades is that of deciding what activities the instruction in science should replace. This decision is not an easy one to make, and presumably the subjects to be replaced or on which decreased emphasis is to be laid would be somewhat different in different schools and in different parts of the world.

There has been just as great reluctance to introduce extensive teaching of science into the field of adult education as into the field of elementary education. The best methods to be used in giving scientific information and instruction in the scientific method to mature individuals who have only an extremely limited background in science probably still need to be discovered. It is likely that a thorough study of existing alternative methods and a search for new ones would yield very important results.

The argument might be presented that it is hopeless to attempt to give the average citizen an understanding of science, because of the complexity of science at the present time and the enormous rate of increase in scientific knowledge. How can even the foremost scientist keep abreast of the rapidly advancing front of knowledge when millions of new facts are being discovered every year? I believe that this pessimism is not justified, and that, indeed, science as a whole is becoming simpler, rather than more difficult. Many parts of physics have already passed through the stage of greatest complexity—the stage at which the body of knowledge in the field consists of an aggregate of largely disconnected facts. With the recognition of relationships among these facts, great numbers of them can be encompassed within a single principle. An understanding of the field as a whole can then be obtained by the process of understanding the general principles. It is not necessary for every fact to be learned; instead a few of the facts can be considered, in order to discover their relationship to the general principles, and thereafter other facts that, for practical or accidental reasons, come to the attention of the individual can immediately be correlated by him with the general principles. At the present time chemistry is making rapid progress toward the ultimate goal of theoretical simplification; chemistry too has passed through the stage of maximum complexity. In biology and the medical sciences much of the fundamental investigational work now going on consists of a search for the fundamental general principles; we may feel confident that before many years have gone by the most significant of these principles will be discovered, and these subjects too will from that time on become progressively simpler.

One way in which an increased knowledge of the nature of the physical and biological world can be of value to the individual citizen is through the conferring on him of an increased equanimity, an increased confidence in natural law and order. The well-being of an individual may be greatly impaired by his fear of the unknown, which may far exceed the fear that he would have of a known danger, which he might prepare to meet in a rational way. In a world in which human beings have achieved extreme powers of destruction of one another, through the use of an astounding new source of energy, the non-understanding individual might well become extremely apprehensive, in such a way as to prevent him from making the correct personal and political decisions, and to cause him to accede without a trace of protest to suggestions or orders from a dictatorial leader.

An incidental advantageous result of scientific education for all people which is of more than negligible significance is the personal satisfaction and pleasure that accompany pure knowledge and understanding. The physical and biological world in which we live is truly astounding and wonderful. No matter what the extent of his general education nor the caliber of his mental abilities, every human being might achieve satisfaction and increased happiness through an increased knowledge and understanding of the world. The sources of happiness in life are not so bountiful that mankind can afford to neglect such an important one. If the ever-present oppressing danger of world war can ultimately be averted, and the world can enter into a continuing period of peace and friendliness, the intellectual activities of the average man may become a source of happiness to him comparable to that provided by his emotions.