A Survey of the Sciences

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THE TITLE WHICH I HAVE CHOSEN FOR this address is a presumptuous one. In a brief half hour we must attempt a survey of the sciences, give some idea of their different natures, tell something about their present doings, and throw a look to their future. To find our way through this difficult task, we shall need some guiding principle. For this purpose let us regard the different sciences as arranged in a hierarchy, on a sort of ladder, in the order of their abstract character. This is a useful principle of arrangement for which we have long been indebted to the French philosopher, Auguste Comte, along with some other good things and some pompous bosh.

At the base of the ladder we place mathematics, the discipline which carries furthest the process of abstraction, by selecting—abstracting out—for study from the real world only the simplest and most general concepts such as those of order, number, and dimensionality. By taking into consideration further concepts abstracted out from the real world, such as those of matter, energy, and electricity, we come to the science of physics. By including the concept of different kinds of substance and of chemical change from one kind to another, we arrive at chemistry. By adding the concepts of a special kind of matter called living and of a special kind of behavior called mental, we come to biology and psychology. And, by including in our study more and more of the complexities of the actual world around us, we could pass on to social psychology, economics, and the social sciences in general. Let us now look at some of these sciences in the order named.

We start with mathematics—so-called Queen of the Sciences. For a mathematician this might mean Queen "over" the Sciences; you remember the dictum of Pythagoras, who said, "All things are number." But for a physicist, like myself, it cannot mean more than Queen "among" the Sciences. There are three things about mathematics of which I wish to speak: its simplicity and generality, its freedom of invention, and its logicality in accomplishment.

The simplicity and generality of mathematics reside in the simple and general character of the elements that it picks out for study. These are such things as order, number, magnitude, dimensionality, functional dependence, proximity, inclusion, and exclusion, which prove on examination to be quite simple and general notions. Thus, the idea of number is a simple and general one, as, for example, the simple three that characterizes these three fingers or the first three men in the front row, and the general three which characterizes all other collections of three objects. Mathematics is sometimes hard for you and me to understand, not because the mathematician chooses complicated things to talk about, but because he says such complicated things about them. As the study of mathematics becomes more profound, the elements selected for study may even tend to become simpler. Finally, they become meaningless p's and q's on a piece of paper which have no properties beyond those contained in the rules chosen for their manipulation, and no function except in testing the internal consistency, rather than the truth, of the results of such manipulation. It is at this stage that Bertrand Russell makes the humorous comment, "Mathematics may be defined as the subject in which we never know what we are talking about nor whether what we are saying is true."

The freedom of invention in mathematics lies in the liberty of the mathematician to create new elements for study by combination, extension, and analogy, and in his liberty to create his own problems for investigation in which he pursues the behavior of his elements to the furthest depths his mind can penetrate. This liberty is highly prized by mathematicians. As Cantor put it, "Das Wesen der Mathematik liegt gerade in ihrer Freiheit" (The essence of mathematics lies just in its freedom). Nevertheless, this freedom has some peculiar consequences. When the mathematician finds that the problem which he has freely created is too hard for solution, he is still free to create an easier one—which he can solve and publish in a paper. With the freedom to set up all sorts of problems for solution it becomes more difficult to distinguish between trivial and important problems; and the doings of mathematicians may become controlled by temporary fashion or by the opinion of influential cliques. Nevertheless, these difficulties are also present to a lesser degree in the other sciences, and we often have to leave it to the future to decide what really was important.

The logicality of mathematics places a true limit on its creative freedom, since, above all else, the mathematician will demand that the results of his studies shall lead to mutually compatible conclusions. Indeed, at a fundamental level the disciplines of logic and mathematics have now tended to merge. On the one hand, this has come about from the invention of symbolic logic—the so-called algebras of logic—which lead logicians and mathe-

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maticians to use the same kind of economical, shorthand language. On the other hand, and more important, it has come about from the contradictions to which mathematics is now being led as it pushes its studies further by what seem to be logical procedures. This means not only that mathematics provides a testing ground for what is logical, but also that the problems of logic have now become fundamental problems for mathematics itself.

This turn of affairs is so important that I shall try to give some idea of the way in which logical difficulties can arise. Mathematicians love to talk about sets of elements, for example, the set of three elements consisting of this pencil, this paper, and this desk—a perfectly simple idea. With their urge to create, they then like to talk about subsets of such a set, such as the subset containing the two members, pencil and paper or pencil and desk—still perfectly simple—or, even more, to create a new set consisting of all subsets containing two members—not quite so simple. In this way they are led to create a so-called set of all sets, which contains among its elements all possible subsets and all sets of such subsets. This leads to an infinite number of elements which is very pleasing to the mathematicians, since the properties of infinity are among the very things that they especially want to study. But now the trouble begins. On a piece of paper no larger than this we define some simple quantities applying to the elements of the set and define what seems to be a sensible subset. By a small computation we then calculate the value of one of our quantities for the subset and, to our amazement, suddenly obtain the value $\frac{1}{2}$ for a quantity which by definition can only have the values 0 and 1. This is no trivial contradiction such as could be obtained by doing something foolish, like dividing by 0 or reasoning from an incorrect geometrical drawing. The mathematicians themselves do not agree as to what is wrong. Perhaps infinity will always make trouble; perhaps we have defined something that cannot exist; perhaps the logical principle of excluded middle is wrong. These are important questions. The presently shaken foundations of mathematical analysis depend upon the answers.

To the abstractions considered by mathematics, physics adds further elements, taken from the real world, which seem of a more palpable character. These include concepts as to physical space and time, the study of which has led to the Einstein theory of relativity; the concepts of mass, momentum, energy, and electricity, whose deeper treatment now finds expression in modern quantum mechanics; and the concept of fundamental structural particles such as electrons and protons, which constitute the subject matter of nuclear physics. The developments of relativity and of quantum mechanics, and progress in nuclear physics, have been the great happenings in physical science during the present century.

The theory of relativity has two branches: the special theory which treats the relativity of uniform motion in a straight line, and the general theory which treats the relativity of all kinds of motion and is thereby led to a theory of gravitation. The ideas of the special theory, obtained by an appreciation of the actual nature of spatial and temporal measurements, have now permeated the whole thinking of physics. We use them every day in the laboratory, for example, in treating the behavior of high-velocity particles or in calculating the energy of nuclear reactions such as those in the atomic bomb. We no longer find it strange that meter sticks should appear shortened and clocks slowed down, when in motion relative to our own measuring instruments. Indeed, we have now found mesotrons in the cosmic rays which, merely because of their high velocities, last 20 times longer than stationary mesotrons before changing over into electrons. It is now only the cranks, like circle squarers and angle trisectors, and Nazi "Aryan" physicists, who still remain worried by special relativity. The rest of us realize the inadequacy of old-fashioned space-time intuitions based on ancestral experience with slow velocities and have actually grown new space-time intuitions which make high-velocity phenomena seem reasonable and right.

The ideas of the general theory of relativity and its theory of gravitation have had much less impact on the ordinary thinking of physics. This is partly due to the fact that the Newtonian theory of gravitation is plenty good enough for the laboratory, and that the three crucial tests of general relativity have to do with small astronomical effects. In addition, the nonlinear equations of general relativity are extremely troublesome to handle, and this has led to a recent attempt at a linear theory of gravitation, for which I cannot myself see adequate motivation. As nearly as I can see the future, the relativity theory of gravitation provides a basis from which we shall go forward, not backward. Recent English opinions that Hubble's observations disprove the relativity treatment of the recession of the nebulae are not sound; the most that such observations could now do would be to disprove the adequacy of some particular model of the universe. In this connection, I have two pleasing bits of astronomical information to impart. Observations on nearby nebulae, made in recent years at Mount Wilson and at Mount Hamilton, now give strong additional evidence for the belief that the red shift in light from distant nebulae is actually due to their motion away from us, as assumed in the relativity treatment. The final figuring of the 200-inch mirror in Pasadena is now so nearly perfect that we can confidently expect its completion this summer. The mirror will then go up to join the telescope mounting, which waits for it on Mount Palomar, and we can look forward with excitement to the new knowledge of the structure of the universe which this greatest of all telescopes will bring.

We must now turn to quantum mechanics, which has given us the greatest advance in theoretical physics since relativity. As in the case of relativity, this advance has resulted from clear thinking with regard to the actual nature of the results of physical measurement; its consequences have now permeated the thinking of the laboratory; and it has led to new and improved ideas concerning the nature of the physical world. The full development of quantum mechanics, however, can not yet be regarded as complete, since so-called infinity difficulties persist when we attempt to push on.

Among the new and improved ideas provided by quantum mechanics are some striking conclusions concerning the true relation between cause and effect. In agreement with the Heisenberg uncertainty principle, we now see that a complete knowledge of the state of a physical system at any given instant is not sufficient to permit an exact prediction of that system's future behavior. The best that we can do is to make statistical calculations concerning the future behavior that can be expected on the average. As a consequence, we now have to regard the true connection between physical cause and effect as a statistical one and give up the idea that the behavior of the physical world is strictly determined.

This still seems very distressing to Einstein, who says, "Der Herr Gott wurfelt nicht" (The Lord God does not throw dice). Most of us, however, are quite content with the outcome. We do not see how any other outcome would be possible in view of the uncontrolled disturbances introduced by the very act of observation. We appreciate that past intuitions as to the exact connection of cause and effect were based on experience with those very situations where the disturbing effects of observation are too small to be noticed. And we are happy that possibilities for statistical prediction still remain, since, without some possibility of prediction, science itself would surely be destroyed. I must caution you, however, that the opinion of one good physicist that the uncertainty principle brings free will and moral responsibility back into the world can hardly be regarded as sensible. As far as I know, moral responsibility has never left the world and, indeed, could hardly be helped by a principle which makes physical happenings, to the extent that they are not determined, take place in accordance with the laws of pure chance.

Now to nuclear physics, where we delightfully arrive at an old-fashioned kind of science in which the experimenters find out new things faster than the theoreticians can predict them, and sometimes in contradiction thereto. The important recent events in this field have been the experimental discovery of the new particles—neutron, positron, and mesotron—now added to the previously known electron and proton, and the experimental study of the properties and behavior of the different kinds of nuclei which are composed from such fundamental particles. It is these different kinds of nuclei which give us the different kinds of atoms and substances that exist in the world. It will be of interest to mention three examples of the interplay between experiment and theory in this field of work.

The existence of the positron—a positively charged electron—had not been theoretically predicted before its discovery in cosmic rays by Anderson, but an existing attempt by Dirac at a theory of the proton was then immediately seen to give at least a partially satisfactory explanation of the positron instead. The existence of a particle like the mesotron had been theoretically assumed beforehand by a Japanese named Yukawa, in order to explain the forces holding protons and neutrons together in nuclei. Actual mesotrons, which are like electrons but 200 times as heavy and with an average life of only 2.15 millionths of a second before they change over into electrons, were then discovered in cosmic rays by Neddermeyer and Anderson, but have so far not proved successful in explaining the forces that hold protons and neutrons together. The disintegration of uranium nuclei by fission, which led to the invention of the atomic bomb, had not been theoretically predicted before its discovery by Hahn and Strassmann. However, immediately on discovery, this phenomenon was seen to be reasonable on the basis of simple theoretical considerations of Bohr as to the nature of heavy nuclei.

I must complete these words on nuclear physics with a remark about a horrible little particle called the neutrino. No direct effect from neutrinos has ever been found; their existence has been assumed merely for the purpose of carrying away energy and momentum that would otherwise seem to be destroyed. This is very unsatisfactory. Perhaps it would be better to abandon the idea of the conservation of energy rather than to invent a new particle that one can never find.

I hope that the foregoing gives some right ideas as to what is happening in physics. There are other things which I should like to talk about, such as the important work of Prof. Lindsay, of this University, on the philosophical bases of physics, but these deep matters will have to be a subject for private conversation with him.

We now come to the science of chemistry, which adds, to the physical notion of the existence of matter in general, the more specific concept of many different kinds of chemical substance and of chemical reaction from one kind of substance to another. In this connection, however, I must now tell you of an important change that has taken place in our thinking. With the help of the new quantum mechanics, and of our new ideas as to the nature of electrons and nuclei, we now find it possible to give an adequate explanation of chemical substance and chemical reaction in terms of the concepts of physics. Thus, a minor revolution has taken place in the organization of science. We now no longer regard chemistry as a science separate from physics but rather as one of the group of physical sciences in which, for example, we also include kinematics, mechanics, and electrodynamics.

I call this revolution a minor one for several reasons. The explanation of chemistry in terms of physics is a revolution that was long impending and, indeed, expected and desired by many chemists, but one which could not be consummated until quantum mechanics had furnished the proper tools. The revolution has not eliminated the necessity of providing different kinds of atoms to explain chemical substances and reactions, but has merely transferred to physics the task of building such atoms out of electrons and nuclei. Finally, the revolution has had little impact on much significant chemical work, since the theoretical possibility of going back to quantum mechanics for explanation is often neither practical nor profitable. Thus, it would often be foolish to describe in quantum-mechanical language the results of the work in physical and inorganic chemistry which has been carried out at Brown University by Prof. Kraus and his colleagues, and which has been so important in peace and in war. Similarly, in the important applications of organic chemistry to biological problems, quantum-mechanical language is not usually appropriate.

Let us now turn to the field of biology. To a physicist who, like myself, still remains a human being, this would seem to be a wonderful science, with possible answers to all the important questions of life. It would be so easy if we could just say that "life" is the new abstraction that must now be added to those of physics and chemistry to get the science of biology, and that this science will then tell us all we want to know about life, death, freedom, and immortality. I think, however, that actually we have to say something much more nearly like the following.

We now add a new kind of abstraction, that of the so-called living organisms. These are material bodies which can maintain themselves, at least for a time and in a properly selected environment, in a substantially steady state through a continuous interchange of matter, energy, and entropy with their surroundings; which are irritable to external stimuli and can adjust to moderate changes in environment; which, under suitable conditions, can exhibit possibilities for growth, change in form, and reproduction in kind; which present themselves to our attention as a series of many different but not unrelated species; and which exhibit the influence of a long past history of evolutionary change as an essential determinant of present structure and behavior.

The difference between biological and physical-chemical work is frequently characterized by the intimate dependence of biological material on its environment and its essential dependence on the specific history of its past evolution. Indeed, the essence of a good physical-chemical experiment, when we are not concerned with cosmological problems, is usually to free the outcome from such dependence. Thus, a mixture of hydrogen and oxygen should explode whether we prepare the gases ourselves and store them in bottles or buy them already prepared and stored in tanks. But the behavior of plants and animals is always delicately dependent on sunlight and food and is essentially dependent on a particular series of evolutionary changes that have taken place in the recent past—in the last 100,000,000 years or often much less.

I wish that I were competent to tell you about the extraordinarily interesting things that are happening in biology. The last sweeping innovation in this field still appears to be the genetic explanation of the factors controlling heredity, given by Morgan and his colleagues. It is comforting to appreciate the extent to which our own behaviors are determined by the genes, provided by our fathers and mothers, since we can't do anything about it ourselves. Recent happenings in genetics include: elaborate mathematical analyses of the rates at which evolutionary changes can take place through gene mutation; laboratory observations on the action of the environment in selecting for survival different mutant forms of bacteria; further experiments on the artificial production of mutations and on the possibility for the specific control of such mutations; and studies of the chemical processes by which genes determine the behavior of the rest of an organism, which have been greatly furthered by Beadle's recent introduction of *Neurospora* as an especially convenient genetic material.

In the field of biochemistry great things are also happening. They include studies on the action of enzymes—hormones, vitamins, and others—in controlling biochemical reactions; advances in immunology, where the lock-and-key-like behavior of antigen and antibody seems significant; further work on the structure of the proteins, where the template-like pattern of complicated molecules plays such an important role; and studies of the tobacco virus and other similar viruses, where such a simple physical-chemical structure is found that we have to regard these substances as lying at the boundary between inert and living matter. To the physicist, biology is the green pasture beyond the fence where it would be good to roll in the long grass.

We must now pass on to psychology, which is the least abstract of the sciences for which we shall have time. Here it would be simple if we could just take "mind" as the further abstraction from reality that has to be added to those of biology to arrive at psychology, but things now become so complicated that the psychologists themselves are not yet well agreed. For myself, I should at the present moment like to say something about as follows. We now add the new abstraction of a special kind of behavior, commonly called mental, which characterizes the activity of individual organisms as a whole, which frequently appears purposive in character, and which includes the verbal behavior of ourselves and of others when giving an introspective account of our own sensations, feelings, and thoughts. Certainly a very poor statement, containing ill-defined and unanalyzed concepts, but at least omitting or covering up in its verbiage that bothersome word "mind." We are indebted to the work of the behaviorists, including the important contributions of Prof. Hunter, of this University, for a view of psychology which emphasizes observable behavior rather than hypothetical mind. This leads at once to the first of two comments on psychology.

As a consequence of the ease with which we often distinguish between what we call physical, and what we call mental, behavior, it seemed natural in the past—and indeed long ago in the past—to introduce the two separate abstractions of body and of mind. By doing so, however, we immediately threw ourselves open to that sea of troubles, the so-called body-mind problem. Having divided our man up into a separate mind and body, what should be the interaction between these two disparate entities, and how should we ever get the whole man back together again? Increasingly in the last years these theoretical difficulties have been augmented through observation and practice in the field of psychosomatic medicine—for example, recognition in military medicine of the psychogenic factors in the nevertheless real rheumatism of soldiers. In general, we often find, on the one hand, unconscious desire to escape into ill health producing the corresponding physical symptoms, and, on the other, the presence of bodily health fostering mental serenity and sanity. In such connections it seems probable that our scientific abstractions will in the future become more appropriate.

The second comment has to do with the revolution in psychology brought about by the psychoanalytic doctrine of Freud. As to this, much controversy has raged, and some academic psychologists are still disturbed, even when the language and explanations of psychoanalysis are already issuing from their lips. From a pragmatic point of view psychoanalysis certainly proves useful—in the treatment of neuroses, in the treatment of a restricted class of psychoses, and, above all, in our daily lives when we must try to understand the motives both of ourselves and of others. Indeed, in view of its present expense, perhaps we ought to say, "What this country needs most is a good five-cent psychoanalysis." The various methods of so-called "short therapy," recently introduced through the exigencies of military psychiatry, may be a step in that direction. From a theoretical point of view much remains to be done. The better incorporation of psychoanalytic doctrine into the main body of psychology must be pursued further; the already-fruitful study of the relations between psychoanalysis and cultural anthropology must be continued; and, above all, the present vigorous development of psychoanalytic theory must not be stopped, even by Freudian scholastics who regard themselves as the only true guardians of the pure faith.

Psychology must be the last of the various sciences to which we give detailed attention. We have now gained a reasonable idea of the kind of things happening in the different sciences and the methods by which we proceed from one science to another by including further features of the actual, concrete world around us. By continuing the procedure we could presumably go on to social psychology and the social sciences in general, although perhaps with considerable difficulty and uncertainty.

So far consideration has been given to the so-called pure sciences, each of which has the task of determining the principles that explain its own particular field of phenomena. We must now give a word to the so-called applied sciences, in which these principles are employed in other fields. For the layman, the term applied science usually implies application to practical or industrial ends, such as the navigation of ships or the manufacture of radios, but for the scientist, the term also includes, as of special interest, the application of the principles of one science to another.

Of all the applied sciences, applied mathematics is the most important, since its methods are needed and used in all the other sciences. This usefulness does not seem surprising, for, as we have seen, mathematics selects for its study those simple and general elements which will also often be present in the situations studied by other sciences. In addition, mathematics has invented such a clear and economical language for the logical treatment of complicated problems that the other sciences also find it useful as they themselves become more complicated. As an illustration, we, nowadays, even find psychologists writing books on that very difficult subject, the mathematical theory of statistics—and they do not do so badly at it either.

In view of the importance of applied mathematics, I wish to pay special tribute to Dean Richardson who, in addition to his own notable contributions to pure mathematics, has had the sagacity and ability to foster the establishment and activities of the Brown University Institute of Applied Mathematics. We may look on the present and future accomplishments of this Institute with satisfaction and confidence.

Just as mathematics, the most abstract of the sciences, can be applied to all the others, each of the various pure sciences can be applied to those that stand above it on the ladder of abstraction. Thus, the applications of physics and chemistry to biology are now proving extremely fruitful in the explanation of biological phenomena that we could not otherwise understand. Indeed, the study of biology with the help of physical-chemical methods is a rich vein which will not be worked out for many decades. This brings us to a consideration of the problem of the extent to which the phenomena of any science can be explained in terms of the more abstract sciences below it. Perhaps all of biology and psychology—life and mind themselves—might be explained in terms of physics and chemistry. This would be pleasing to some persons, including some pretty good scientists.

This important question, as to the extent to which a given science can be explained in terms of more abstract ones, is always present in my own thinking. I believe that the answer depends on the extent to which the science in question has really introduced genuinely new abstractions from reality, beyond those already incorporated in the preceding sciences below it. On this basis, I myself feel led to the following tentative conclusions: on the one hand it is my conviction that the phenomena of biology and psychology will never be found to contradict the principles of physics and chemistry. On the other hand, it is my belief that such principles will perhaps not prove sufficient for the full explanation of biology and will almost certainly not be sufficient for the explanation of psychology.

Finally, I wish to say something about the application of the sciences to so-called practical ends. In the first flush of enthusiasm for the industrial revolution that resulted from the practical applications of science, it was felt that the consequences of such application could only be for the good of man. As we have seen more of these consequences, however, and thought more deeply on such matters, we now realize that the practical results of science will be good or evil, in the ethical sense, depending on the nature of the application. This conclusion is dramatically illustrated in the scientific development of atomic energy which can be used either for peaceful or destructive purposes. The possibilities for evil are clear in the development of a weapon which could be used, in a surprise attack before any declaration of war, for the destruction of a score of cities and most of the inhabitants thereof.

The evils that can result from wicked application do not mean that science itself is evil. Each pure science merely gives an objective account of the facts which it finds in its own field of study. These facts are ethically neutral; it is only their application that can lead to evil rather than good results. Moreover, from a broader and deeper point of view, the pursuit of these ethically neutral facts must itself be regarded as a good. It is a spiritual good, since knowledge of the true nature of the world in which he lives should increase the intellectual dignity of man. It is a practical good, since it is only through knowledge of the actual facts that men of good will can plan for their application to good rather than evil ends. Keeping certain facts secret, as in the field of atomic energy, can be temporarily important and serve a useful purpose, but can make no fundamental contribution to the prevention of evil.

In the control of evil, psychology and the social sciences have a special role to play. This resides in the provision of information and advice concerning the human and social consequences of different courses of action—for example, in establishing international control of atomic energy. It does not reside in any ethical quality pertaining to these sciences themselves. The objective findings of psychology are as ethically neutral as those of any other science and can be applied not only to good but also to evil ends, as in determining the most effective form for sinful propaganda such as that of the Nazis. Even when the anthropologist studies the moral practices and systems of different tribes and nations, his findings remain objective and ethically neutral and contain, as science, no recommendation of one set of moral values over another. Science is concerned with judgments of existence, not judgments of value.

The judgments of men and of nations of men as to what is good depend partly on the static factors of childhood training and of prevailing custom, but partly also on the dynamic consequences of the new spiritual insights which determine the teachings of ethical leaders and which each of us may sometimes experience in the closet of his conscience. As the judgment is being reached, science can advise as to the nature of the facts. When the judgment is being advocated, science can point out its consequences. When the judgment is being implemented, science can supply tools for the accomplishment. But in its final essence, ethical judgment is a creative activity of man.

It is my faith that the ethical insight and scientific intelligence of man are such that the control of evil is possible. I am sure that humanity will continue to encounter great troubles, but I do not think that civilization will destroy itself. To surmount our troubles, we shall need courage, patience, clarity of thought, and sincerity in the advocacy of fair and reasonable courses of action. For these virtues we may pray, each in his own fashion.