Atom Man and the Universe

THE LONG CHAIN OF COMPLICATIONS

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Would you that spangle of Existence spend
About THE SECRET—*quick about it, Friend!*
A Hair perhaps divides the False and True—
And upon what, prithee, may life depend?

THE RUBAIYAT OF OMAR KHAYYAM

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I

How Natural Science Works

Man has a deep-rooted impulse to relate himself to the world he inhabits. Not only does he ask how the world is constructed, how it was created, and what will become of it, but, more important, what is his own position in the world's Grand Design? Throughout human history, he has attempted to answer these questions, but since he was not present at the creation, cannot see into the future, and has not yet conquered outer space, his total knowledge, or assumed knowledge, of the world has been limited to speculation. This speculation is necessarily based on observation.

Man's first and most primitive assumptions about his world were based upon accidental observations on his immediate environment, which were more or less arbitrarily combined into an often elaborate fantasy. For example, the theory on the origin of the earth and of man that we are most familiar with is that in the book of Genesis. It was obviously the prevalent view at the time and place in which the book was written, and it was therefore incorporated into it. Because of the strong religious and cultural significance that the Bible still exerts, this assumption continues to be important, though our expanded knowledge has long since made it appear unreasonable. The systematic collection and treatment of observations, which we call natural science, has provided us with a basis for our speculations about the world that is entirely different from that of several thousand years ago. In this book we will discuss those results of natural science that are most important in this respect.

But, first of all, we shall examine the ways in which natural science works and the goals it sets up for itself.

The great industrial revolution that started in the Western world during the nineteenth century is in great part the result of natural science. The science of electricity has given us electric lights, electric motors, the telephone, radio, and television; chemistry has contributed a great variety of new materials; biology has created new medical techniques and improved grains. The fruits of science have also been used for inventing increasingly horrible means of destruction. All this has led many people to believe that the purpose of science is mainly technological advancement—that the task of science should be to produce better television sets, more durable nylon stockings, and more effective atomic bombs.

This is a misrepresentation. The goal of natural science is first and foremost to satisfy human curiosity by finding out how the world around us actually looks and by bringing order into our chaos of experiences and observations. It is true that what we learn about nature makes it possible for us to use it and master it, but this is not the primary objective of science. For example, the prerequisites for inventing a radio were a knowledge of the laws of electromagnetism, the discovery of radio waves, and an understanding of how the properties of electrons were made use of in a transistor. But Maxwell did not set forth the laws of electromagnetism with any thought of their practical application; and neither Hertz, who discovered radio waves, nor Thomson, who discovered the electron, dreamed of what their work would one day make possible. To take another example, much of the progress in nuclear physics was made during the years between the two world wars. Although it was this progress that created the scientific conditions necessary for the atomic bomb, none of those who carried out the work had any thought of such a result. It was not until they felt the impact of the Second World War that they reluctantly used their knowledge in the service of war technology.

The conversion of science to technology was the result of inventive activity and, to a larger degree, of its systematic derivative, which we call applied research. In spite of the admitted practical significance of applied research, we shall nevertheless devote what follows exclusively to the "impractical" side of science.

The great volume of scientific work has made radical specialization necessary. A chemist, an astronomer, or a botanist does not understand much about the others' fields. However, specialization is being counteracted to some degree by the increasing interest in the fruitful border areas between the different sciences that have been opened up in recent times. Thus astronomy and physics have been combined into astrophysics: ever since physicists discovered the relationships that exist between the spectrum generated by a light source and the properties of this light source, astronomers have been able to draw very important conclusions about the composition of the stars by analyzing the spectra of starlight. Similarly, a combination of physics and chemistry has yielded physical chemistry; and the application of chemistry to biological problems has initiated the extremely fruitful field of research that we call biochemistry.

But even within each scientific discipline, specialization has resulted from the necessity of applying many different methods to a single subject. This specialization has produced three different types of scientists.

The first group includes the sample collectors and the systematizers. They investigate flowers, birds, insects, or rocks, which they catalog; they analyze and synthesize known and unknown chemical compounds; they count stars and classify them; or they make precision measurements of spectral lines and calculate the energy states of atoms. It is this group that is responsible for the traditional image of scientist: incredibly diligent, precise, absorbed in his work and therefore quite introverted. This is the group that constructs the solid basis for all of science.

The second group might be characterized as the engineers of science. Their task is to invent and construct the increasingly complicated instruments that science requires. They are the men obsessed with records: for them scientific progress is measured by the maximum pressure of the highest temperature that can be achieved, by the resolution of the latest giant telescope, or by the particle energy attained in the most modern accelerator. It is they who widen the limits of science and make it possible to study ever more remote star systems, or particles with yet shorter lives. They send up the satellites and design the spaceships. Because their activity is extremely expensive, funds must be acquired; and if the work is to be useful to science, the projects selected must be truly important. Since publicity is essential to the acquisition of funds, this type of scientist has, of the three, become the most prominent in the public eye. Their rise to the fore is naturally aided by the fact that many people are much more easily impressed by the world's largest, most majestic, and most beautifully built telescope than by the characteristics of insignificant stars that the telescope is built to investigate.

The theoreticians form the third group. Their function is to treat the results obtained by the first two groups, expressing them in as clear and precise a form as possible: in other words, to construct a theory. To them the aim of science is to summarize as much experience as possible, to demonstrate that even the most widely disparate occurrences may be essentially similar and merely unlike aspects of one fundamental phenomenon. Although the names of the great theoreticians are well known, not everyone understands the way in which they work. Some of their work is related to artistic activity: for both the artist and the scientist sort the essential from the chaos of sensory impressions, and render this in as concentrated and elegant a form as possible. Just as the painter expresses his thoughts and experiences in colors, the sculptor in clay, and the musician in notes, so the practitioners of the art of science use formulas and laws that—like anything that offers a concentrate of the world we live in—exhibit a high degree of beauty. The highest praise a theoretician can receive, when he shows a new formula to a colleague, is the enthusiastic cry, "Very beautiful!" In reality the beauty of the formula differs no more from that of music than the beauty of music does from that of painting. It is true that the vision of science as art is a most exclusive experience, and is enjoyable onlv after many long years of study; but a correct interpretation of an atonal symphony or a cubist painting also requires a certain amount of preparation—the taste must first be cultivated and specialized in a given direction. The Greeks numbered astronomy among the fine arts, and its Muse was Urania. The other natural sciences were not included because they were not yet in existence at the time that Mnemosyne's nine famous daughters were born.

Although it is obviously impossible to describe an activity as variegated and richly faceted as science in one small paragraph, we can say that scientific work takes place in the following way: When investigation of an area of research begins—whether the field has been known for a long time or whether it is a new one initiated by a series of recent discoveries—attempts to anticipate which laws might apply within that area are quickly made. Hypotheses are propounded, and these are gradually formed into theories that are at least partly worked through. The theories are intended to summarize all the facts that have been found and even to predict the results of new investigations. If the predictions are subsequently verified a theory is "confirmed," but if it is not confirmed, it must be replaced by another theory. Not infrequently, two or more neighboring areas can be covered by a common theory, and it is consequently desirable to generalize theories so that they summarize all the results within as large an area as possible.

That summary of experience constituting a theory must be formulated in a way that, although often abstract, is extremely concise. Science is therefore in need of a language that makes concentrated and logical formulation possible. Mathematics is such a language. Mathematical formulas make it much easier to express a theory exactly, and with the help of mathematical methods one can analyze the content of a theory and predict its consequences. It has been suggested many times that man would not have been able to think logically if no language existed. Whether this is true or not, it is obvious that ordinary language does greatly facilitate organized thought. And the language of mathematics is an even greater aid to the formulation of scientific thought. The "mathematical apparatus," as the system of formulas and arithmetic laws that mathematicians have put at the disposal of natural science is called, is indispensable for unifying complicated arguments and deductions.

Although all theories *can* be formulated in ordinary language, most of them would lack the sharpness and elegance that mathematics makes possible. An entire book may be required to express in words that which is contained in half a line of formula. The translation of a mathematical formula into literary language is certainly more difficult than even the translation of Chinese poetry, and the beauty of certain formulas is always lost.

One often hears the assertion that a theory is "mathematically proven." This expression is misleading. It is equivalent to maintaining that there is a mathematical proof that grass is green. A theory is a summary of observations, and its validity, or lack of it, can be ascertained only by comparing it and its implications with observations. Mathematics is invaluable for making it possible to survey all the implications of a theory with certainty and clarity, but the final "proofs" of a theory's accuracy can be provided only by observations.

As an example of how natural science works we shall discuss some of the developments that took place in the history of physics. Although many important natural laws had been discovered by the Mediterranean, Indian, and Chinese philosophers, Galileo's discovery of the laws governing the motion of a falling object is considered by many to be the birth of modern physics. Of perhaps greater significance than the formulation of these laws were the new principles of scientific thinking that were introduced in the process. The most important objective for Galileo was not to find out *why* a stone fell, but *how* it fell—what were the laws explaining its increase in velocity, and what described the relationship between the height from which an object fell and the duration of the fall? In other words, he realized that it was not essential to determine the "ultimate cause" of an event, and he confined himself to a study of the event itself. As a result of this differentiation, a division between metaphysics and physics was made and it has existed ever since. The function of physics, then, as well as that of the other natural sciences, is the description and coordination of occurrences rather than the "explanation" of them. Science tries to relate to one another as many widely different phenomena as possible, to demonstrate that all are actually unlike aspects of one and the same thing; but this is not exactly the same as "understanding" these phenomena.

Astronomy evolved in much the same way as Galileo's mechanics, and after the introduction of the Copernican system, Kepler was able to set forth his famous laws of planetary motion summarizing a very large number of observations of the planets' motions in the heavens. In his analyses, Kepler relied so heavily on Tycho Brahe's extraordinarily precise (for that time) measurements of the planets' positions, that one might say his laws are a synthesis of all the measurements made by Tycho Brahe in the course of many years of clear nights.

Astronomy and the science of falling bodies, which had previously been separate disciplines, were combined by Newton, who showed that Galileo's law of falling motion and the planetary laws could be seen as special cases of much more general laws that were applicable to the motions of all bodies: for a stone dropped from a tower, for a meteorite falling toward the earth, for the planets that moved in the heavens. Newton's great synthesis, usually called *classical mechanics* today, was extended and deepened during the eighteenth century, revealing for the first time a large area within which all phenomena could be calculated in detail according to a single basic law. By applying this single law (which in mathematical symbols fills half a line) we can determine the motions of the moon and the planets in the sky, the place at which a hurled projectile will land, the height and magnitude of the waves created by a steamship, the tone and the sonority of a flute, or the maximum cargo of an airplane. The significant test, then, of classical mechanics has been the revelation that all these apparently widely disparate phenomena are indeed merely unlike aspects of the same phenomenon.

The science of electricity (electrodynamics), too, began as two separate sciences: electrostatics, which treated those phenomena that occurred when a bit of amber or a glass rod became electrically charged by rubbing it; and magnetostatics, the study of magnets and magnetic fields. After Galvani and Volta had shown that electricity could be produced with chemical elements, and Ørsted subsequently found that the electrical current produced in this way had magnetic effects, these fields were combined. The founder of electrodynamics was Maxwell, whose famous equations summarized completely the extensive field as it existed in his time. But there was more to come. When Maxwell examined the implications of his equations he found that, among other things, they predicted a wave motion of an electromagnetic nature. In attempting to verify Maxwell's predictions, Hertz did find such waves (which we now call radiowaves). After it was demonstrated that light, too, was an electromagnetic wave motion, optics (the science of light) became a branch of electrodynamics. From the study of optics we have learned that such differing effects as the refraction of light in a lens or its reflection by a mirror, and the functioning of an electric motor or a television set, are all explained by the one natural law that is formulated in Maxwell's equations.

Both classical mechanics and electrodynamics were largely closed chapters by the end of the nineteenth century. With the advent of the twentieth century, a chaotic period for physics began. New discoveries made it possible to study atomic structures, and it was soon apparent that events taking place in the microworld of the atom were not governed by the same laws that applied to the phenomena that had been studied up to that time. The motions of the electrons, which circled the minuscule but heavy nucleus, did not conform to the laws of classical mechanics. Quantum mechanics (or wave mechanics), which was developed during the 1920's, supplied the answers to our questions about electrons, and as a result we are now well informed about the structure of the atom outside the nucleus.

Quantum mechanics can be considered a generalization of classical mechanics, or, conversely, classical mechanics can be regarded as a special case of quantum mechanics. As soon as we begin to work with such extremely "small" phenomena as the structures of atoms, we must employ quantum mechanics; but for calculating the motions of larger bodies, quantum mechanics always gives the same results as classical mechanics.

This, then, is how the scientist works. He first looks for those laws which apply within a certain area, and when he has found them he tries to extend them to new areas. Occasionally the laws can be applied without being changed, as were Maxwell's electromagnetic laws to light phenomena. At other times, the laws must be made more general before two areas can be combined, as were those of the field of mechanics when it was combined with atomic physics. It can be said that the ultimate goal of natural science is to discover a single law or formula that will explain all experiences and all observations. We do not know how long we will have to work, before this goal is attained—certainly a very long time. But we have already gone a good part of the way: this is evident in certain quite large and important areas, such as electrical science, in which all known phenomena have already been summed up in a single law.

Let us assume that we did find the "ultimate law" of nature we seek, so that we could proudly assert, "In this way the world is constructed." Immediately a new question is raised: what lies behind this law, *why* is the world constructed in just that way? This "why" leads us beyond the limits of natural science, and into the area of metaphysics or religion. A physicist, as an expert, should answer with an *ignorabimus:* we do not know and can never know. Others would say that God