The Crisis of Science

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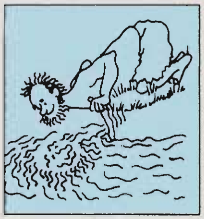

Reflections carries material on the history and future of science, its methodology and philosophy, and its connections with other human activities. It is intended to provide a broad view, complementing the more specific discussions of individual topics in the rest of the journal.

A new age in physics has dawned from the beginning of the 20th century. Let us make a few general comments on the historical development of physics before we proceed to analyze the characteristics of this new age.

It is perhaps not an exaggeration to state that modern science began with Newton. Before the time of Newton, many isolated facts were known about the physical world in a disconnected fashion. From time immemorial, man has been collecting such knowledge which might be of practical use in his daily life or which might lead to greater efficiency and productivity in the crafts and the trades. But the only example of a pure science in the ancient world was mathematics. Especially geometry was a subject which commanded the attention of scientific thinkers. The ancient Greeks and their followers developed certain approaches and methods for the study of geometry. Later scientists attempted to apply these same approaches and methods to study material objects. That is why Euclid is revered as the father of all exact sciences. It was Newton who first showed that motions of material bodies can be studied by the mathematical methods previously applied only to geometry. The central problem of dynamics is to find out how the future configurations and motions of material bodies can be predicted from a knowledge of their present configurations and motions.

Newton found the solution to this problem of dynamics. His successors demonstrated that his laws hold sway from the stars in the sky to terrestrial objects of different sizes around us. The results and predictions based on these laws gave remarkable agreement with what was directly observed. It

Translator's Note

This is an essay which appeared in the Bengali magazine *Parichay* in the issue of August-September 1931. S N Bose, the creator of quantum statistics, always had the conviction that we ought to present science to the common man in his own language. In later life, he nurtured a Bengali magazine for popular science. His interest in presenting science in Bengali, however, began quite early in life. The present essay is his first published writing in Bengali at a time when quantum mechanics was in its infancy. In brilliant and lucid Bengali prose, he provides a masterly account of the developments of physics which led to the quantum crisis. This is truly an extraordinary piece of popular science writing in every sense. Perhaps it will be difficult to find a comparable essay in any Indian language where a master of such stature describes to laymen a recent revolution in his field of research. Bose's colleague, M N Saha, did a considerable amount of non-technical writing in English, which appeared in the magazine *Science and Culture*. Since Bose's non-technical writings are all in Bengali, his talents as a popularizer of science are not generally known outside his native Bengal. This translation may give some idea of his style and presentation.

It may be noted that this essay was written before the discovery of the neutron. Bose therefore considers electrons and protons to be the only constituents of matter. I should also mention that I have followed Bose in referring to electromagnetic waves as waves in the ether. As one of the first translators of Einstein's papers on relativity into English, Bose must have been aware that the concept of ether was no longer so useful. Perhaps he felt that a lay person would grasp the concept of waves in ether more easily than the concept of electromagnetic waves. One may also note that Bose, in his characteristic modest way, never even mentions his own famous work of 1924 which could have quite naturally found a place in this essay.

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became possible to predict at which point in the sky a planet would appear two years from now by doing calculations today. One could also predict the trajectory that a cannon ball would follow and find out exactly where it would land behind the enemy lines. Encouraged by these successes, the scientists began investigating other aspects of the material world. Heat, light and electricity became the phenomena to be studied next. Following the footsteps of Newton, later scientists tried to carry on similar mathematical investigations of these phenomena and achieved a fair degree of success.

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ultimate constituents of matter. The human mind has pondered over the question whether there is some kind of fundamental building block out of which the whole physical world with all its apparent diversity is made up. A long tradition of research has finally culminated in the modern view of chemistry that everything around us has resulted from different combinations of only 92 elements. These elements are the constituents of all material objects starting from wood and stones to the bodies of animals. To demonstrate the correctness of this assertion, chemists are able to synthesize more and more substances artificially in their laboratories.

At one time it was a complete mystery to scientists how complex substances are produced by natural transmutation processes - sometimes deep down under the Earth's surface, sometimes within the living bodies of animals. Modern chemical analysis has shown that all these substances are made up from the same elements, and chemists have now succeeded in synthesizing many of them starting from the basic elements. A search for the laws governing these analyses and synthesis processes has given rise to a scientific atomic theory. The modern scientific view is that all solids, liquids and gases are made up of atoms. Whether a substance is found in the solid, liquid or gaseous state merely depends on the motions and mutual interactions of the atoms. To establish this point of view with certainty, scientists had to address the question whether the dynamics of the invisible atoms is governed by the same laws of mechanics which govern the dynamics of visible objects around us. Towards the end of the 19th century, Thomson, Rutherford and other scientists came to the conclusion that these 92 elements themselves must contain two types of subatomic particles. One of them is the positively charged particle proton, whereas the other is the negatively charged particle electron. It seems that all atoms are made up of just these two fundamental particles. Scientists have arrived at this conclusion by a kind of scientific analysis, which in some ways reminds us of the analysis through which the chemists had earlier established the existence of 92 elements.

This view of the ultimate constitution of matter became firmly established by the turn of this century. The main task of physics today is to discover the laws which determine how these two types of charged particles make up the atoms of all the different elements. Experiments performed by Rutherford and others at the beginning of the century suggested that the structure of the atom resembles the structure of the solar system in which the planets revolve around the Sun obeying Newton's laws of motion. It appears that each atom has a nucleus within which positively charged particles outnumber negatively charged particles. Several negatively charged electrons revolve around this nucleus in different orbits. The net positive charge of the nucleus equals the total negative charge of the electrons in all the orbits. Consequently the whole atom appears as an uncharged entity in experiments which do not resolve the subatomic structure. Since all the fundamental particles possess the same quantity of charge, the 92 different elements essentially differ because of the different numbers of orbiting electrons within their atoms. The heaviest metal has 92 electrons moving round the nucleus. Rutherford and others have provided strong evidence in support of this model of the atomic structure. The properties of different elements can be explained from the different electronic structures of their atoms. It is becoming increasingly clear that many macroscopic properties of bulk matter are related to the electrical charges of the subatomic particles. But we still do not fully understand the laws of physics which govern the motions of electrons around the nucleus.

At this point, it is essential to examine some concepts which physicists had developed from their studies of heat and light. Since a solid is perceived by the physicist as a collection of

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many vibrating molecules, it is natural to conclude that heat is nothing but the macroscopic manifestation of the motions of molecules. When we keep one end of a metal rod in a furnace, the other end also gradually gets heated. The explanation for this is that the energetic molecules of the furnace collide with the less energetic molecules of the initially cooler rod and transfer some energy to them. The interactions amongst the molecules of the rod then transmit this energy to the end of the rod away from the furnace. A substance appears hotter when the molecules inside are more energetic. Scientists are trying to explain different thermal properties of matter on the basis of this idea. This has naturally led to the discussion whether Newtonian mechanics is applicable to the motions of molecules. Calculations based on Newtonian mechanics have given some promising results. Here, however, one has to keep in mind that it is not possible to carry out detailed calculations of the motions of all molecules the way it was done for the planets. We have seen that one can predict the future motions of planets from a knowledge of their positions and velocities at some instant of time. It is impossible to have such detailed knowledge for all the molecules within a material body. We are able to say something definite in spite of this limitation only because we are dealing with a very large number of molecules. In order to understand bulk properties of matter, it is not essential to have exact knowledge about each and every molecule. If we merely know the laws which in general govern the motions of the molecules, then that is often sufficient to explain many of the thermal properties. We can give the example of a country in which millions of people live. Even though we may not have detailed information about the occupations of all the people, we can still study the general economic prospects of the country and its statistics of births and deaths. Often this limited knowledge suffices to draw many important inferences. In exactly the same way, we can study the motions of molecules within some bulk material from a statistical point of view.

Physicists have the faith that the laws of Newtonian mechanics have the same kind of definiteness as the axioms of geometry and other branches of mathematics. When calculations based on these laws gave fantastic agreement with experiments, scientists expected that any ideal scientific theory should have a similar kind of definiteness. Our discussion in the previous paragraph should make it clear that such definiteness is not expected in the theory of heat. Today when the physicists are viewing the whole material world as collections of electrons and protons, and are trying to explain all phenomena from the electrical interactions of these fundamental particles, it is not clear that the laws they are arriving at should have the same definiteness as the axioms of geometry. Some of the current ideas of physics should be taken more as working hypotheses which yield results in agreement with experiments. On some future occasion, I wish to elaborate upon the differences between the axioms in a subject like geometry and some of the current laws of physics which are more of the nature of provisional working hypotheses.

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Space provides the stage on which electrons and protons act as the *dramatis personae*. There was a time when physicists used to think of electrons and protons as ordinary material spheres in every respect apart from the very small size. Since the sizes of these subatomic particles appeared much smaller than the atom, it seemed natural to conclude that an atom has mostly empty space inside. Physicists started thinking about the nature of the empty space when it was realized that most properties of light can be understood adequately by assuming light to be some kind of wave motion in space. From the beginning of the 19th century, a hypothesis started gaining ground that the whole universe is filled with some continuous substance called *ether*. The atoms or subatomic particles are then floating in this ocean of ether. Light is nothing but the waves in this ocean. There can be waves of different wavelengths in this ocean, which all propagate with the same speed

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in vacuum. The different colours of light are caused by the differences in the frequencies of these waves. Today scientists know of ether waves which are both much larger and much smaller than the waves which produce the sensation of light in our eyes. Today man has learnt some techniques by which waves of certain types can be started in ether. The radio waves, which carry information over thousands of miles, are examples of such man-made waves in the ether. These waves are much larger than the ordinary waves of light. On the other hand, the X-rays, which are now being widely used in medicine, are also waves in the ether which are much smaller in size.

Although the Moon, the Sun, the planets and the stars are very far from the Earth, they are all linked by being immersed in the same ether. We receive the light from the stars and the nebulae through the waves in the ether. The ether transmits the heat and the light from the Sun to us as well, making the Earth vibrate with life, enabling man both to harness the energy and to misuse it for different purposes. Much of the energy coming from the Sun has been transformed and stored in diverse forms on the surface of the Earth. The main conclusion of modern physics is that all the phenomena occurring in the natural world can ultimately be understood in terms of the interactions amongst the fundamental particles inside the atom and their interactions with the waves in the ether. The primary goal of 20th century physics is to discover all the laws governing such interactions.

This brief outline of how physics developed from the time of Newton to the 20th century provides an exmaple of the unending strivings of the human mind. By the 18th century, the mathematical scientists who followed Newton managed to solve most of the problems of planetary astronomy by applying the laws of mechanics. Newtonian mechanics already came to be regarded as the supreme example of an ideal physical theory. It was thought as inconceivable that there could be limitations to Newtonian mechanics. The scientists of that period thought that the one or two still unresolved problems of planetary astronomy merely reflected their inability to apply the principles of mechanics properly. Well into the 19th century, physicists kept nurturing the view that any physical theory should be based on a few fundamental principles having the same kind of definiteness as the axioms of geometry or Newton's theory of gravitation. With the development of the atomic theory of heat, physicists started recognizing the importance of statistical theories which were somewhat different in nature from the previous theories. At the end of the 19th century, it became necessary to think anew what the nature of a physical theory ought to be. Finally the study of light precipitated the ultimate crisis. Let me mention only this: when the well-known laws of dynamics were applied to study the interactions of light with atoms, the results were in complete disagreement with experiments. This led Planck to propose the quantum theory in 1900. The central idea of this theory is the following. Although most of the previous results of optics were consistent with the wave theory of light, Planck showed that we have to adopt a different point of view when we consider the emission or absorption of light by atoms. Although the propagation of light can be understood best from the wave theory, it is necessary to regard light as a stream of particles when we study the interaction of light with atoms.

Just the way chemists were earlier led to the atomic theory of matter while studying the reactions amongst different chemical substances, the study of reactions between light and matter led to the particle theory of light. According to quantum theory, light beams of different colours have different types of quanta. The energy carried by a quantum depends on the frequency of light, and typically one quantum is removed from the beam of light when an atom absorbs energy from the

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beam. On the other hand, when the atom gives out energy, a quantum is produced. These ideas are completely contrary to what we expect in Newtonian physics. Niels Bohr and other physicists are trying in the last few years to develop a framework within which the quantum theory can be reconciled with the older ideas of physics.

Let me again summarize the nature of the crisis in optics. The questions arising from the study of propagation of light can be answered only by the wave theory, the particle theory being unable to handle these questions. On the other hand, questions pertaining to the creation or destruction of light can be answered adequately only by the particle theory. The wave theory fails completely in these situations. This crisis in physics has deepened further in the last four or five years as a result of some startling new discoveries pertaining to the nature of electrons. Although we were so far regarding electrons as very small particles, the experiments by a few scientists like Davisson and Germer showed that sometimes a beam of electrons can act like a wave. Just as light can be diffracted to give rise to fringes, a beam of electrons can produce similar patterns on hitting an obstacle.

All these developments have caused a revolution in physics in recent years. Neither material particles nor light can be treated according to our previous notions. Although we were accustomed to regarding electrons as tiny particles of charge, we are suddenly becoming aware that they can also behave like waves. On the other hand, light can no longer be considered simply as a wave, since it often behaves like a beam of particles.

A consequence of this revolution is that none of the laws of physics are now regarded as sacrosanct. We have got enough evidence that Newtonian mechanics does not hold in the world of atoms. So scientists are now busy examining the foundations of all the theories of physics. Efforts are being made to ascertain which laws can still pass as scientific truth and which laws have to be rejected as being mere scientific constructions that served the earlier scientists. The concepts of space and time are also under scrutiny. All of physics is based on measurements connected with space, time and motion. One pertinent question is whether our theories can be based on some hidden quantities which are not measured. This is an age of critical self-questioning in physics. Physicists are now desperately trying to come to terms with many of the concepts, which were accepted without question in the 19th century when classical physics dazzled everyone with its brilliant and spectacular triumphs.

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Bachelier got there first ... The first person to discover the connection between random walks and diffusion was Louis Bachelier, in a doctoral dissertation of 1900. The examiners, damning it with faint praise, gave it a *mention honorable* at a time when only a *mention très honorable* was considered worth having. Bachelier wasn't studying Brownian motion, however; he had his eye on something closer to the gambling origins of probability theory—the random fluctuations of the Paris stock-market. It's perhaps no surprise that a failed thesis on stocks and shares attracted little attention from theoretical physicists. In 1905 Albert Einstein laid what everyone thought were the foundations of the mathematical theory of Brownian motion; and Norbert Wiener developed these extensively. Only much later was it discovered that Bachelier had anticipated many of their main ideas!

Poisson's work ranged from calculus to criminal law ... Poisson paid considerable attention to the application of probability theory to criminal jurisprudence. He even wrote a treatise titled "A Study of Verdict Probability in Criminal and Civil Cases".